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Ferrohydrodynamic and magnetohydrodynamic effects on ferrofluid flow and convective heat transfer

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ABSTRACT

In this paper, influence of an external magnetic field on ferrofluid flow and heat transfer in a semi annulus enclosure with sinusoidal hot wall is investigated. The governing equations which are derived by considering the both effects of FHD (Ferrohydrodynamic) and MHD (Magnetohydrodynamic) are solved via CVFEM (Control Volume based Finite Element Method). The effects of Rayleigh number, nanoparticle volume fraction, Magnetic number arising from FHD and Hartmann number arising from MHD on the flow and heat transfer characteristics have been examined. Results show that Nusselt number increases with augment of Rayleigh number and nanoparticle volume fraction but it decreases with increase of Hartmann number. Magnetic number has different effect on Nusselt number corresponding to Rayleigh number. Also it can be found that for low Rayleigh number, enhancement in heat transfer is an increasing function of Hartmann number and decreasing function of Magnetic number while opposite trend is observed for high Rayleigh number.

1. Introduction

The CVFEM (Control Volume based Finite Element Method) uses the benefits of both finite volume and finite element methods for simulation of multi-physics problems in complex geometries [1] and [2]. Sheikholeslami et al. [3] studied the problem of free convection between a circular enclosure and a sinusoidal cylinder. They concluded that streamlines, isotherms, the number, size and formation of the cells inside the enclosure strongly depend on the Rayleigh number, values of amplitude and the number of undulations of the enclosure. Sheikholeslami et al. [4] used heatline analysis to simulate two phase nanofluid flow and heat transfer. Their results indicated that the average Nusselt number decreases as buoyancy ratio number increases until it reaches a minimum value and then starts increasing. MHD (magnetohydrodynamic) effect on natural convection heat transfer in an enclosure filled with nanofluid was studied by Sheikholeslami et al. [5]. Their results indicated that Nusselt number is an increasing function of buoyancy ratio number but it is a decreasing function of Lewis number and Hartmann number. Sheikholeslami et al. [6] used CVFEM to simulate the effect of magnetic field on free convection in an inclined half-annulus enclosure filled with Cu–water nanofluid. Their results showed that Hartmann number and the inclination angle of the enclosure can be considered as control parameters at different Rayleigh number. Also this method is used in order to simulate different scientific problems [7–15].

Cooling capabilities of heat transfer equipments have been constrained because of the low thermal conductivity of conventional heat transfer fluids. However, it is well known that, metals in solid form heavy orders-of-magnitude higher thermal conductivities than those of fluids. Therefore, the thermal conductivities of fluids that contain suspended solid metallic particles could be expected to be significantly higher than those of conventional heat transfer fluids. The goal of nanofluid is to achieve the highest possible thermal properties at the smallest possible concentrations by uniform dispersion and stable suspension of nano particles (preferably <10 nm) in host fluids. Nanotechnology provides new area of research to process and produce materials with average crystallite sizes below 100 nm called nano materials. Sheikholeslami and Ganji [16] investigated two phase modeling of nanofluid in a rotating system with permeable sheet. They found that Nusselt number has direct relationship with Reynolds number and injection parameter while it has reverse relationship with Rotation parameter, Schmidt number, Thermophoretic parameter and Brownian parameter. Asymmetric laminar flow and heat transfer of nanofluid between contracting rotating disks was studied by Hatami et al. [17]. Their results indicated that temperature profile

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Nomenclature

A	amplitude
B	magnetic induction ($=\mu_0 H$)
C_p	specific heat at constant pressure
Ec	Eckert number ($=(\mu_f\alpha_f)/[(\rho C_P)_f \Delta T L^2]$)
En	heat transfer enhancement
Gr_f	Grashof number($= g\beta_f \Delta T(r_{\text{out}} - r_{\text{in}})^3/\upsilon_f^2$)
$\vec{g}$	gravitational acceleration vector
H_x,H_y	components of the magnetic field intensity
H	the magnetic field strength
Ha	Hartmann number ($= \mu_0 H_0 L\sqrt{\sigma_f/\mu_f}$)
k	thermal conductivity
K′	constant parameter
$L\neq$	gap between inner and outer boundary of the enclosure $L = r_{\text{out}} - r_{\text{in}}$
Mn_F	Magnetic number arising from FHD ($=\mu_0 H_0^2 K'(T_h - T_c) L^2/(\mu_f\alpha_f)$)
M	magnetization($= K'\overline{H}(T_c' - T)$)
Nu	Nusselt number
Pr	Prandtl number($=\upsilon_f/\alpha_f$)
r	non-dimensional radial distance
Ra	Rayleigh number ($=g\beta_f\Delta T(r_{\text{out}} - r_{\text{in}})^3/\alpha_f\upsilon_f$)
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

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($=4\pi\times 10^{-7}$ Tm/A)
υ	kinematic viscosity
ψ&Ψ	stream function & dimensionless stream function
Θ	dimensionless temperature
ρ	fluid density
β	thermal expansion coefficient
ω,Ω	vorticity & dimensionless vorticity

Subscripts

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

becomes more flat near the middle of two disks with increase of injection but opposite trend is observed with increase of expansion ratio. Nanofluid convective heat transfer becomes a popular topic in last decade [18–38].

Magnetic nanofluid (Ferrofluid) is a magnetic colloidal suspension consisting of base liquid and magnetic nanoparticles with a size range of 5–15 nm in diameter coated with a surfactant layer. Jue [39] used semi implicit finite element method in order to simulate magnetic gradient and thermal buoyancy induced cavity ferrofluid flow. Their results showed the flow strength increases with the strengthening magnetic field. 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 [40]. They found that the effect of cylinder rotation on the local Nusselt number distribution is more pronounced at low Reynolds number. Nanjundappa et al. [41] studied the effect of MFD (magnetic field dependent) viscosity on the onset of ferro convection in a ferrofluid saturated horizontal porous layer. They showed the nonlinearity of fluid magnetization has no influence on the stability of the system. The vortex dynamics behind various magnetic obstacles and characteristics of heat transfer were investigated by Zhang and Huang [42]. They found that the pressure drop penalty was not increasingly dependent on interaction parameter. Azizian et al. [43] studied the effect of an external magnetic field on the convective heat transfer and pressure drop of magnetite nanofluids under laminar flow regime conditions. They showed that the mechanisms for heat transfer enhancement are postulated to be accumulation of particles near the magnets. Natural convection in a rectangular enclosure containing an oval-shaped heat source and filled with Fe_3O_4/water nanofluid was investigated by Moraveji and Hejazian [44]. Free convection of ferrofluid in a cavity heated from below in the presence of magnetic field was studied by Sheikholeslami and Gorji [45]. They found that particles with a smaller size have better ability to dissipate heat, and a larger volume fraction would provide a stronger driving force which leads to increase in temperature profile.

Parametric analysis and optimization of entropy generation in unsteady MHD flow over a stretching rotating disk was investigated by Rashidi et al. [46]. Rahman et al. [47] studied the augmentation of natural convection heat transfer in triangular shape solar collector by utilizing water based nanofluids having a corrugated bottom wall. They found that both Grashof number and solid volume fraction have significant influence on streamlines and isotherms in the enclosure. The effects of using different geometrical parameters with the combination of nanofluid on heat transfer and fluid flow characteristics in a HCTHE (helically coiled tube heat exchanger) were numerically investigated by Mohammed and Narrein [48].They found that counter-flow configuration produced better results as compared to parallel-flow configuration. Free convection heat transfer in a concentric annulus between a cold square and heated elliptic cylinders in presence of magnetic field was investigated by Sheikholeslami et al. [49]. They found that the enhancement in heat transfer increases as Hartmann number increases but it decreases with increase of Rayleigh number. Rashidi et al. [50] studied the effects of magnetic interaction number, slip factor and relative temperature difference on velocity and temperature profiles as well as entropy generation in MHD (magnetohydrodynamic) flow of a fluid with variable properties over a rotating disk. Ellahi [51] studied the MHD flow of non-Newtonian nanofluid in a pipe. He observed that the MHD parameter decreases the fluid motion and the velocity profile is larger than that of temperature profile even in the presence of variable viscosities. Rashidi et al. [52] considered the analysis of the second law of

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