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Heat flux boundary condition for nanofluid filled enclosure in presence of magnetic field

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ABSTRACT

In this paper, effect of magnetic field on free convection heat transfer in an enclosure filled with nanofluid is studied. KKL (Koo-Kleinstreuer-Li) correlation is used for simulating effective thermal conductivity and viscosity of nanofluid. The inner cylinder is maintained at uniform heat flux and the outer cylinder has constant temperature. The governing equations are solved via Control Volume based Finite Element Method. The heat transfer between cold and hot regions of the enclosure cannot be well understood by using isotherm patterns so heatline visualization technique is used to find the direction and intensity of heat transfer in a domain. Effect of Hartmann number, volume fraction of nanoparticle, Rayleigh number and aspect ratio on streamline, isotherm and heatline are examined. The results show that as Hartmann number increases Nusselt number decreases while opposite trend is observed as nanoparticles volume fraction, Rayleigh number and aspect ratio increase. Domination of conduction mechanism causes heat transfer enhancement to increase. So enhancement in heat transfer increases with increase of Hartmann number and aspect ratio while it decreases with augment of Rayleigh number.

1. Introduction

Essential tasks such as pumping or mixing of fluids in micro devices can be achieved by means of an electromagnetic body force (a Lorentz force) produced by the interaction of an applied magnetic field and an electric current that usually is externally supplied. Rudraiah et al. [1] investigated numerically magnetic field effect on natural convection in a rectangular enclosure. They found that the magnetic field decreases the rate of heat transfer. Al-Najem et al. [2] calculated the flow and temperature fields under uniform magnetic field in a tilted square cavity with isothermal vertical and adiabatic horizontal walls. They demonstrated that the suppression effect of the magnetic field on convection currents and heat transfer is more significant for low inclination angles and high Rayleigh numbers. Ece and Buyuk [3] examined the laminar natural convection flow in the presence of a magnetic field in an inclined rectangular enclosure heated and cooled on adjacent walls. They found that the magnetic field suppressed the convective flow and the heat transfer rate. 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. [4]. They found that the enhancement in heat transfer increases as Hartmann number increases but it decreases with increase of Rayleigh number. MHD effect on natural convection heat transfer in an inclined L-shape enclosure filled with nanofluid was studied by Sheikholeslami et al. [5]. They found that enhancement in heat transfer has reverse relationship with Hartmann number and Rayleigh number.

Control volume based finite element method (CVFEM) is a scheme that uses the advantages of both finite volume and finite element methods for simulation of multi-physics problems in complex geometries [6–11]. Sheikholeslami et al. [12] performed a numerical analysis for natural convection heat transfer of Cu–water nanofluid in a cold outer circular enclosure containing a hot inner sinusoidal circular cylinder. They concluded that in the absence of a magnetic field, the enhancement ratio decreases as the Rayleigh number increases; while an opposite trend is observed in the presence of a magnetic field.

Conceptually, convective flow and heat transfer are affected by nanofluid properties such as viscosity and thermal conductivity. Conventional heat transfer fluids, including oil, water, and ethylene glycol mixture are poor heat transfer fluids, since the thermal conductivity of these fluids plays an important role on the heat transfer coefficient between the heat transfer medium and the heat transfer surface. An innovative technique for improving heat transfer by using solid particles in the fluids has been used extensively during the last decade. The term nanofluid refers to these kinds of fluids by suspending nano-scale particles in the base fluid and has been introduced by Choi [13]. The particles are different from conventional

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Nomenclature

B	Magnetic field
C_p	Specific heat at constant pressure
Gr_f	Grashof number
Ha	Hartmann number $\left(=LB_x\sqrt{\sigma_f/\mu_f}\right)$
Nu	Nusselt number
Pr	Prandtl number $(=\upsilon_f/\alpha_f)$
T	Fluid 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	Length of outer enclosure
$\overrightarrow{g}$	Gravitational acceleration vector
q''	Heat flux
Ra	Rayleigh number $(=g\beta_f q'' L^4/(k\,\alpha_f\upsilon_f))$

Greek symbols

ξ	Angle measured from the horizontal middle plane
ω,Ω	Vorticity & dimensionless vorticity
λ	Angle of magnetic field
σ	Electrical conductivity
α	Thermal diffusivity
$\varnothing$	Volume fraction
μ	Dynamic viscosity
υ	Kinematic viscosity
ψ&Ψ	Stream function & dimensionless stream function
Θ	Dimensionless temperature
ρ	Fluid density
β	Thermal expansion coefficient

Subscripts

c	Cold
h	Hot
loc	Local
ave	Average
nf	Nanofluid
f	Base fluid
s	Solid particles
in	Inner
out	Outer

particles (millimeter or micro-scale) in that they keep suspended in the fluid. Nanotechnology is deemed as one of the significant forces that drives the next major industrial revolution of this century. It represents the most relevant technological cutting edge currently being explored. It aims at manipulating the structure of the matter at the molecular level with the goal for innovation in virtually every industry and public endeavor including biological sciences, physical sciences, electronics cooling, transportation, the environment and national security. Khanafer et al. [14] seem to be the first who have examined heat transfer performance of nanofluids inside an enclosure taking into account the solid particle dispersion. Sheikholeslami et al. [15] used heatline analysis to simulate two phase simulation of 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. Rashidi et al. [16] considered the analysis of the second law of thermodynamics applied to an electrically conducting incompressible nanofluid flowing over a porous rotating disk. They concluded that using magnetic rotating disk drives has important applications in heat transfer enhancement in renewable energy systems. Sheikholeslami et al. [17] used the lattice Boltzmann method to examine free convection of nanofluids. They found that choosing copper as the nanoparticle leads to obtain the highest enhancement for this problem. Also their results indicate that the maximum value of enhancement occurs in $\lambda = 2.5$ at $Ra = 10^6$ while for other Rayleigh numbers it is obtained at $\lambda = 1.5$. Ellahi [18] studied the magnetohydrodynamic (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. Sheikholeslami et al. [19] analyzed the magnetohydrodynamic nanofluid flow and heat transfer between two horizontal plates in a rotating system. Their results indicated that, for both suction and injection Nusselt number has a direct relationship with nanoparticle volume fraction. Recently several authors investigated about nanofluid flow and heat transfer [20–28].

In the present work MHD effect on natural convection heat transfer is investigated in an enclosure. KKL model is used in order to simulate effective thermal conductivity and viscosity of nanofluid. The effects of nanoparticles volume fraction, Rayleigh number, Hartmann number and aspect ratio on flow and heat transfer characteristics are investigated. In addition, heatline visualization technique is used to show where heat is transferred from hot to the cold regions by convection and conduction.

2. Geometry definition and boundary conditions

The physical model along with the important geometrical parameters is as shown in Fig. 1(a). The width and height of the enclosure is L. The outer cylinder is maintained at constant cold temperature T_c, whereas the inner circular wall is under constant heat flux. To assess the shape of inner circular and outer rectangular boundary which consists of the right and top walls, a supper elliptic function can be used as follows

$$\left(\frac{X}{a}\right)^{2\hat{n}}+\left(\frac{Y}{b}\right)^{2\hat{n}}=1. \qquad (1)$$

When $a = b$ and $\hat{n} = 1$ the geometry becomes a circle. As $\hat{n}$ increases from 1 the geometry would approach a rectangle for $a \neq b$ and square for $a = b$. It is also assumed that the uniform magnetic field $(\overrightarrow{B} = B_x\overrightarrow{e_x} + B_y\overrightarrow{e_y})$ of constant magnitude $B = \sqrt{B_x^2 + B_y^2}$ is applied, where $\overrightarrow{e_x}$ and $\overrightarrow{e_y}$ are unit vectors in the Cartesian coordinate system. The orientation of the magnetic field forms an angle λ with horizontal axis such that $\lambda = B_x/B_y$. In this study, λ equals to zero. electric current J and the electromagnetic force F are defined by $J = \sigma\left(\overrightarrow{V}\times\overrightarrow{B}\right)$ and $F = \sigma\left(\overrightarrow{V}\times\overrightarrow{B}\right)\times\overrightarrow{B}$, respectively.

3. Mathematical modeling and numerical procedure

3.1. Problem formulation

The flow is steady, two-dimensional, laminar and incompressible. The radiation, viscous dissipation, induced electric current and Joule heating are neglected. The magnetic Reynolds number is assumed to be small so that the induced magnetic field can be neglected compared to the applied magnetic field. Neglecting displacement currents, induced magnetic field, and using the

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