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Magnetohydrodynamic free convection of Al_2O_3–water nanofluid considering Thermophoresis and Brownian motion effects

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ABSTRACT

In this study MHD effect on natural convection heat transfer in an enclosure filled with nanofluid is investigated. The transport equations used in the analysis took into account the effect of Brownian motion and thermophoresis parameters. The Navier Stokes equations in their vorticity-stream function form are used to simulate the flow pattern, isotherms and concentration. The governing equations are solved via Control Volume based Finite Element Method. The inner and outer circular walls are maintained at constant temperatures while two other walls are thermally insulated. 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 ($Ha = 0, 30, 60$ and 100), buoyancy ratio number ($Nr = 0.1$–4) and Lewis number ($Le = 2, 4, 6$ and 8) on streamline, isotherm, isoconcentration and heatline are examined. Also a correlation for Nusselt number corresponding to active parameters is presented. The results indicate that Nusselt number is an increasing function of buoyancy ratio number but it is a decreasing function of Lewis number and Hartmann number. Also it can be concluded that as buoyancy ratio number increases the effects of other active parameters are more pronounced.

1. Introduction

Heatline technique is an important method to visualize heat transport in enclosures. Isotherms are used to show the temperature distribution in a domain, however, it is not easy to realize the direction and intensity of heat transfer particularly in convection problems in which path of heat flux is not perpendicular to isotherm due to convection effect. Heatline is a useful tool for visualization and analysis of not only direction but also intensity of heat transfer in a domain. They provide corridors in where heat is transferred from hot to the cold regions by convection and/or conduction. This technique was first proposed by Kimura and Bejan [1] to visualize heat transport for convective heat transfer. Basak et al. [2] studied the natural convection in porous trapezoidal enclosures for uniformly or non-uniformly heated bottom wall by presenting, streamlines, isotherms and heatlines. They observed that heatlines are affected with Darcy number. Oztop et al. [3] used heatline visualization technique to understand heat transport path in an inclined non-uniformly heated enclosure filled with water based CuO nanofluid. Based on the heatline patterns, they observed three heat transfer regions. Numerical investigation of natural convection within porous square enclosures has been performed by Ramakrishna et al. [4]. They illustrated from distribution of heatlines that significant heat transport occurs from hot bottom wall to the top portion side walls at higher Darcy number. Sheikholeslami et al. [5] 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.

Magnetic field influence on natural convection has great importance in many industrial applications such as crystal growth, metal casting and liquid metal cooling blankets for fusion reactors. Rudraiah et al. [6] investigated numerically the effect of magnetic field on natural convection in a rectangular enclosure. They found that the magnetic field decreases the rate of heat transfer. Oztop et al. [7] studied the MHD natural convection in an enclosure from two semi-circular heaters on the bottom wall. Their results showed that flow strength decreases with increase of Hartmann number;

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Nomenclature

C_p	specific heat at constant pressure
D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
$\vec{g}$	gravitational acceleration vector
Ha	Hartmann number $(= HB_x\sqrt{\sigma/\mu})$
k	thermal conductivity
L	gap between inner and outer boundary of the enclosure $(=r_{out} - r_{in})$
Le	Lewis number $(= \alpha/D_B)$
Nb	Brownian motion parameter $(= (\rho c)_p D_B(\phi_h - \phi_c)/(\rho c)_f \alpha)$
Nt	thermophoretic parameter $(= (\rho c)_p D_T(T_h - T_c)/[(\rho c)_f \alpha T_c])$
Nu	Nusselt number
Pr	Prandtl number $(= \mu/\rho_f \alpha)$
r	non-dimensional radial distance
Ra	thermal Rayleigh number $(= (1 - \phi_c)\rho_{f_0} g\beta L^3(T_h - T_c)/(\mu\alpha))$
Nr	buoyancy ratio number $(= (\rho_p - \rho_0)(\phi_h - \phi_c)/[(1 - \phi_c)\rho_{f_0}\beta L(T_h - T_c)])$
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

Greek symbols

ζ	angle measured from the insulated right plane
α	thermal diffusivity
φ	volume fraction
σ	electrical conductivity
μ	dynamic viscosity
υ	kinematic viscosity
ω, Ω	vorticity and dimensionless vorticity
ψ and Ψ	stream function and dimensionless stream function
Θ	dimensionless temperature
ρ	fluid density
β	thermal expansion coefficient

Subscripts

c	cold
h	hot
loc	local
ave	average
in	inner
out	outer

means that magnetic field can be used as a control parameter for heat and fluid flow. MHD effect on natural convection heat transfer in an inclined L-shape enclosure filled with nanofluid was studied by Sheikholeslami et al. [8]. They found that enhancement in heat transfer has reverse relationship with Hartmann number and Rayleigh number. Ellahi [9] 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. [10] analyzed the magnetohydrodynamic nanofluid flow and heat transfer between two horizontal plates in a rotating system. Mahmoudi et al. [11] studied the entropy generation and enhancement of heat transfer in natural convection flow and heat transfer using Copper (Cu)–water nanofluid in the presence of a constant magnetic field. They observed that the entropy generation is decreased when the nanoparticles are present, while the magnetic field generally increases the magnitude of the entropy generation. 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. [12]. They found that the enhancement in heat transfer increases as Hartmann number increases but it decreases with increase of Rayleigh number.

The above literature review reveal that the existence of magnetic field has a noticeable effect on heat transfer reduction under natural convection while in many engineering applications increasing heat transfer from solid surfaces is a goal. At this circumstance, the use of nanofluids with higher thermal conductivity can be considered as a promising solution. The nanofluid can be applied to engineering problems, such as heat exchangers, cooling of electronic equipments and chemical processes. Almost all of the researchers assumed that nanofluids treated as the common pure fluid and conventional equations of mass, momentum and energy are used and the only effect of nanofluid is its thermal conductivity and viscosity which are obtained from the theoretical models or experimental data. These researchers assumed that nanoparticles are in thermal equilibrium and there are not any slip velocities between the nanoparticles and fluid molecules, thus they have a uniform mixture of nanoparticles. Khanafer et al. [13] conducted a numerical investigation on the heat transfer enhancement due to adding nanoparticles in a differentially heated enclosure. They found that the suspended nanoparticles substantially increase the heat transfer rate at any given Grashof number. Rashidi et al. [14] considered the analysis of the second law of thermodynamics applied to an electrically conducting incompressible nanofluid fluid 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 and industrial thermal management. Mixed convection and entropy generation of nanofluids flow in an open cavity heated from below with uniform temperature was numerically investigated by Mehrez et al. [15]. They found that the heat transfer and the entropy generation increase with the increase of Reynolds number, Richardson number and volume fraction of nanoparticles, and vary with the aspect ratio of the cavity and nanoparticle types. Recently several authors investigated about nanofluid flow and heat transfer [16–34].

All the above studies assumed that the nanoparticle concentration is uniform. It is believed that in natural convection of nanofluids, the nanoparticles could not accompany fluid molecules due to some slip mechanisms such as Brownian motion and thermophoresis, so the volume fraction of nanofluids may not be uniform anymore and there would be a variable concentration of nanoparticles in a mixture. Nield and Kuznetsov [35] studied the natural convection in a horizontal layer of a porous medium saturated by a nanofluid. Their analysis revealed that for a typical nanofluid (with large Lewis number) the prime effect of the nanofluids is via a buoyancy effect coupled with the conservation of nanoparticles, the contribution of nanoparticles to the thermal energy equation being a second-order effect. Khan and Pop [36] published a paper on boundary-layer flow of a nanofluid past a stretching sheet. They indicated that the reduced Nusselt number is a decreasing function of each dimensionless number. The problem of double stratification on boundary layer flow and heat transfer induced due to a nanofluid over a vertical plate was investigated by Ibrahim and Makinde [37]. The boundary layer flow and heat transfer over a permeable stretching sheet due to a nanofluid with the effects of