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Hall current effects on MHD free convection nanofluid over an inclined hot plate with viscous dissipation

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Abstract

Numerical study is conducted to investigate the heat and mass transfer of MHD free convection of nanofluid with viscous dissipation and Hall current effects. The numerical method is utilized to study the effects of Hall parameter, viscous dissipation with consideration of free convection. The governed partial differential equations have been reduced to ordinary differential equations. The reduced ordinary differential equations have been numerically solved by Keller Box method. Influence of different involved dimensionless flow parameters on dimensionless velocity, micropolar, temperature and nano particle volume fraction profiles are examined. With an increasing of Brownian motion parameter and thermophoresis parameter the temperature profile is increasing and the nano particle volume fraction profile is decreasing. With the increase of Hall current parameter the velocity and temperature are increasing but the micropolar fluid motion and nano particle volume fraction profiles are decreasing.

Key words: Hall current, nanofluid, Keller Box method and MHD, inclined hot plate, matlab code.

1 Introduction

The study of Magnetohydrodynamics (MHD) flow has many physical applications as well as industrial applications such as generators and pumps. The interaction between the electrically conducting fluid and magnetic field affects the boundary layer flow. MHD boundary layers observed in many technical systems employing liquid metal and plasma flow transverse of magnetic fields. Rashidi *et al.*[1] Studied the entropy generation in steady MHD flow due to a rotating porous disk in a Nanofluid. Ferdows[2] introduced a similarity analysis for the forced and free convection boundary layer flow in a semi-infinite expanse of an electrically conducting viscous incompressible fluid past a semi-infinite non conducting porous plate with suction applying a uniform magnetic field normal to the plate. MHD boundary-layer flow over a stretching surface with internal heat generation or absorption was studied by Basiri Parsa *et al*.[3]. Gnaneswara Reddy[4] analyzed thermophoresis, viscous dissipation and joule heating effects on steady MHD heat and mass transfer flow over an inclined radiative isothermal permeable surface with variable thermal conductivity. Kavitha *et. al*.[5] studied the Suction/ Injection Effects on MHD Flow of a Non-Newtonian Power-Law Fluid Past a Continuously Moving Porous Flat Plate with Heat Flux and Viscous Dissipation. B.S Reedy *et.al.*[6] studied the MHD boundary layer flow of a non-Newtonian power-law fluid on a moving flat plate. Srihari *et. al*.[7] analyzed the MHD free convection flow of an incompressible viscous dissipative fluid in an infinite vertical oscillating plate with constant heat flux. Kishan et. al [8] studied The effects of mass transfer on the MHD flow past an impulsively started infinite vertical plate with variable temperature or constant heat flux.

On the other hand, MHD flow with combined heat and mass transfer has numerous applications in chemical, mechanical and biological sciences. Some important applications are stellar and solar structures, cooling of nuclear reactors, radio propagation and aerodynamics, and power generation system. Soundalgekar *et al.*[9] made an exact analysis to study the conjugate effects of heat and mass transfer on the MHD flow of a viscous fluid past an impulsively started vertical plate. MHD flow and mass diffusion past an impetuous started vertical plate with variable temperature was considered by Rajput and Kumar[10].

Current advances and important in the subject of Hall current involve hall accelerators, flight MHD and MHD generators, nuclear power reactors. The Hall current IC switch or sensors are extremely useful to detects the presence or absence of a magnetic field and gives a digital signal for on and off. Huge values of Hall current parameter in the presence of heavy-duty magnetic fields corresponds to Hall current, which is how, it shakes the current density and allows one to understand the impact of Hall current on the flow studied by Nowar[11]. The study of magneto hydrodynamics flows with Hall currents has important engineering applications in problems of magneto hydrodynamic generators and of Hall accelerators as well as in flight magneto hydrodynamics. Siddiqui *et al.*[12], studied effects of Hall current and heat transfer on MHD flow of a Burgers fluid due to a pull of eccentric rotating disks. Hayat *et al*.[13] studied Hall effects on peristaltic flow of a Maxwell fluid in a porous medium. The effect of Hall currents on interaction of pulsatile and peristaltic transport induced flows of a particle fluid suspension that had been examined by Gad[14]. The analytical solution for Hall and ion-slip effects on mixed convection flow of couple stress fluid between parallel disks is considered by Srinivasacharya and Kaladhar[15]. Narayana *et al*.[16] studied the effects of Hall current and radiation absorption on MHD micropolar fluid in a rotating System. Srinivas *et. al*.[17] studied the effects of Hall current on unsteady MHD flows.

Choi and Eastman[18] have firstly used the nano particles to enhance thermal conductivity of fluids and heat transfer rate. nanofluids have very important industrial applications. Such fluids used to increase the heat transfer rate of microelectronics and microchips in computer devices. Koo and Kleinstreuer[19] deduced experimentally a new conductivity model due to Brownian motion effect by taking the conductivity as a function of temperature and nano particles concentration. Chon *et al*.[20] deduced a modified model depending on concentration, temperature and nano particles size for Cuo and Al_2O_3, thermal conductivity enhancement. Ravikanth and Debendra[21] obtained experimentally a new empirically correlation by dividing the conductivity to two terms statics due to Maxwell model and dynamics due to Brownian motion depending on temperature, concentration, and nano particles size. Sattar and Hossain[22] investigated the unsteady free convective flow with Hall currents and mass transfer past an accelerated vertical porous plate in the presence of a transverse magnetic field while assuming the plate temperature and concentration to be functions of time. Kishan *et. al*.[23]

investigated effects of radiation and heat source/sink of boundary layer flow of MHD nanofluid on an exponentially permeable stretching sheet. Kalyani *et. al*.[24] analysed the results of MHD nanofluid with stagnation point flow in the direction of radially stretching with convectively heated disk along with viscous dissipation. Marripala *et. al.*[25] discussed the effects of thermal conductivity and heat source/sink of micropolar nanofluid flow over radiative stretching surface Mahatha[26] studied the two dimensional steady hydromagnetic boundary layer flow of a viscous, incompressible and electrically conducting nanofluid past a stretching sheet with Newtonian heating, in the presence of viscous and Jou le dissipations. Pal[27] studied the unsteady mixed convection boundary layer flow of an electrically conducting fluid over a stretching permeable sheet in the presence of transverse magnetic field, thermal radiation and non-uniform heat source/sink effects. Motsa and Shateyi[28] considered the problem of magneto micropolar fluid flow, heat and mass transfer with suction through a porous medium is numerically analyzed. Comprehensive reviews on thermo elasticity of micropolar bodies and materials have been made by researchers including Marin[29–31]. Modified Darcy's law for a nanofluid including the Hall current has been used for the modelling. In fact, the Hall effect is an important when the Hall parameter is high. This happens when the magnetic field is strong. In most cases, the Hall term has been ignored in applying Ohm's law as it has no marked effects for small and moderate values of the magnetic field. However, the current trend in the application of magnetohydrodynamics is towards a strong magnetic field, so that the influence of electromagnetic force is noticeable. Under these conditions, the Hall current is important and it has marked effects on the magnitude and direction of the current density and consequently on the magnetic-force term. Therefore, it is important to study the effect of the Hall current on the flow.

The present paper deals with the MHD free convection heat and mass transfer flow of an electrically conducting incompressible nanofluid over a semi infinite inclined hot plate under the influences of applied magnetic field with viscous dissipation and Hall current effects.

2 Formulation of the problem and similarity analysis:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \vartheta\frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty)\cos\alpha + g\beta^*(C - C_\infty)\cos\alpha - \frac{\sigma B_0^2}{\rho(1+m^2)}(u+mW) \tag{2}$$

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} = \vartheta\frac{\partial^2 w}{\partial y^2} + \frac{\sigma B_0^2}{\rho(1+m^2)}(um - W) \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} + \frac{\mu}{\rho c_p}\left(\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right) + \frac{\sigma B_0^2}{\rho c_p}(u^2 + w^2) + \tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y} + \frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right] \tag{4}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} + + \frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial y^2}\right) \tag{5}$$

where u and v are the velocity components along x and y directions and w is the secondary velocity component along z-axis, T, T_w and T_∞ are the fluid temperature, the stretching sheet temperature and the free stream temperature respectively while , C, C_w and C_∞ are the corresponding concentrations, m is the hall parameter, k is the thermal conductivity of the fluid, C_p is the specific heat with constant pressure, α is the angle of inclination, μ is the coefficient of viscosity, ν is the kinematic viscosity, σ is the electrical conductivity, ρ is the fluid density, β is the thermal expansion coefficient, β^* is the concentration expansion coefficient, B_0 is the magnetic field intensity, U_0 is the steam velocity, g is the acceleration due to gravity, D_m is the coefficient of mass diffusivity and D_T is the coefficient of thermal diffusivity respectively. The above equations are subject to the following boundary conditions.

$u=U_0$, $v=0$, $w=0$, $T=T_w$, $C=C_w$, at $y=0$,

$$u \to 0, \quad v \to 0, \quad T \to T_\infty, C \to C_\infty, as\, y \to \infty \tag{6}$$

To convert the governing equations into a set of similarity equations, we introduce the following similarity transformation:

$$W = U_0 g(\eta), \quad \eta = y\sqrt{\frac{U_0}{2\nu x}}, \quad \psi = \sqrt{2\nu x U_0}\, f(\eta),$$

$$\theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty}, \quad \varphi(\eta) = \frac{C-C_\infty}{C_w-C_\infty} \tag{7}$$

$$u = \frac{\partial\psi}{\partial y}, \quad v = -\frac{\partial\psi}{\partial x}$$

From the above transformations, the non-dimensional, nonlinear and coupled ordinary differential equations are obtained

$$f''' + ff'' + Gr\theta\cos\alpha + Gm\varphi\cos\alpha - \frac{M}{1+m^2}(f' + mg) = 0 \tag{8}$$

$$g'' + fg' + \frac{M}{1+m^2}(mf' - g) = 0 \tag{9}$$

$$\theta'' + \eta Prf\theta' + PrEc\left(f''^2 + g'^2\right) + PrEcM\left(f'^2 + g^2\right) + Nb\theta'\varphi' + Nt\theta'^2 = 0 \tag{10}$$

$$\varphi'' + Scf\varphi' + \frac{Nt}{Nb}\theta' = 0 \tag{11}$$

The transform boundary conditions:

$$f = 0, \quad f' = 1, \quad g = 0, \quad \theta = 1, \quad \varphi = 1 \; at \quad \eta = 0$$

$$f' = g = \theta = \varphi \to 0 \quad as \quad \eta \to \infty \tag{12}$$

Where f', g, $\theta and \varphi$ are the dimensionless primary velocity, secondary velocity, temperature and nano particle volume fraction respectively, η is the similarity variable, η_∞ is the value of η at which boundary conditions is achieved, the prime denotes differentiation with respect to η.

Also

$$M = \frac{2x\sigma B_0^2}{\rho U_0}, \quad Gr = \frac{2g\beta(T_w - T_\infty)x}{U_0^2}, \quad Gm = \frac{2g\beta^*(C_w - C_\infty)x}{U_0^2}, \quad Pr = \frac{\mu c_p}{k},$$

$$Sc = \frac{\nu}{D_m}, \quad Ec = \frac{U_0^2}{c_p(T_w-T_\infty)}, \quad Nb = \frac{\rho c_p \tau D_B(C_w-C_\infty)}{k}, Nt = \frac{\rho c_p \tau D_T(T_w-T_\infty)}{k\, T_\infty}$$

are the magnetic parameter, Grashof number, modified Grashof number, Prandtl number, Schmidt number, and Eckert number, Brownian motion and Thermophoresis parameter respectively.

3 Results and Discussions

Numerical calculation for the distribution of primary velocity and secondary velocities, temperature and nano particle volume fraction profiles across the boundary layer for different values of parameters are carried out by using the implicit finite difference scheme known as Keller Box method, it is second order accuracy method. For the purpose of our simulation we have chosen M = 0.5, m = 0.3, Pr = 1.0, Gr = -2.0, Gm = -2.0, Ec = 0.2, Sc = 0.22, and $\alpha = 60^o$ while the parameters are varied over range as shown in the figures. The effects of various parameters on velocity, micropoalr, temperature and nano particle volume fraction profiles are shown in figures.

From figure 1(a)-(d) depicts that with the increasing of angle of inclination the velocity, micropolar fluid and nano particle volume fraction profiles are decreasing while the temperature is increasing. Because of the multiplication of cosá the effects of buoyancy force increases for the α.

In figures 2 (a)-(c) we seen that the effects of magnetic parameter on various flow parameters that the primary velocity profile starts from maximum value at the surface and then decreasing until it reaches to the minimum value at the end of the boundary layer for all the values M. It is interesting to note that the effect of magnetic field is more prominent at the point of peak value, because the presence of M in an electrically conducting fluid introduces a force like Lorentz force which acts against the flow if the magnetic field is applied in the normal direction as in the present problem. As a result velocity profile is decreased. With the increasing magnetic parameter the velocity and nano particle volume fraction profile are decreasing. But the temperature profile is increasing with the increase of magnetic parameter. Here there is no effect on micropolar fluid motion since in the equation has no magnetic parameter.

Figure3(a)-(d)shows the influences of Hall parameter on velocity, micro polar fluid, temperature and nano particle volume fraction profile. With the increase of Hall current parameter the velocity and temperature are increasing, where as the micropolar fluid motion and nano particle volume fraction profiles are decreasing. Hall currents (*m*) tends to accelerate the fluid velocity throughout the boundary layer region which is consistent with the fact that Hall currents induces flow in the flow field.

Figures 4(a)-(b) depicts that the effects of Brownian motion parameter on temperature and nano particle volume fraction profile. With an increasing of Brownian motion parameter the temperature profile is increasing and the nano particle volume fraction profile is decreasing. It clear from the figure that with an increasing of Brownian motion parameter Nb the velocity, micropolar fluid motion and temperature profiles are increasing, where as the concentration boundary layer reduces as Nb increases which there by enhances the nano particles concentration at sheet.

Figures 5(a)-(b) shows that with the increasing of thermophoresis parameter the temperature profile is increasing while reverse trend is observed away from the boundary. But the nano particle volume fraction profile is decreasing.

Figure 6(a)-(b)Eckert number characterizes the relationship between a flow's kinetic energy and the boundary layer enthalpy difference, from the figures we analyze that the temperature profile and the nano particle volume fraction profiles are decreasing with an increase of Eckert number.

Figure 7(a)-(b) we can observe that the effects of Schmidt number on the temperature profile and nano particle volume fraction profile, Schmidt number is the ratio of fluid boundary layer to mass transfer boundary layer thickness. Therefore the figures depict that with the increasing of Schmidt number the temperature profile and the nano particle volume fraction profile are increasing.

Figure 8(a)-(b) depicts that the effect of Prandtl number on temperature and nano particle volume fraction profile. With an increase of Prandtl number the temperature profile and nano particle volume fraction profile is increasing. For the small value of Prandtl number the rate of thermal diffusion is more than the rate of momentum diffusion.

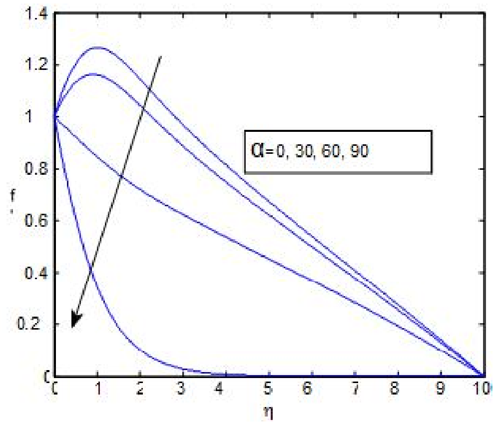

Figure 1(a) effects of α on velocity profile

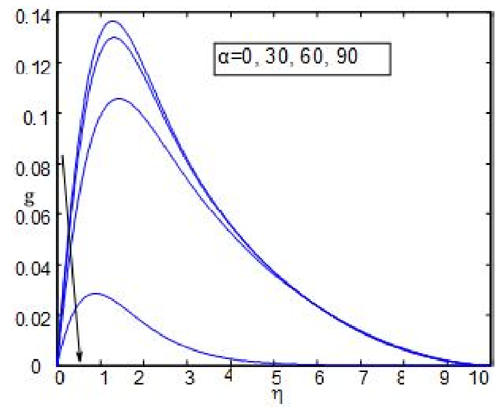

Figure 1(b) effects of α on micropolar fluid profile

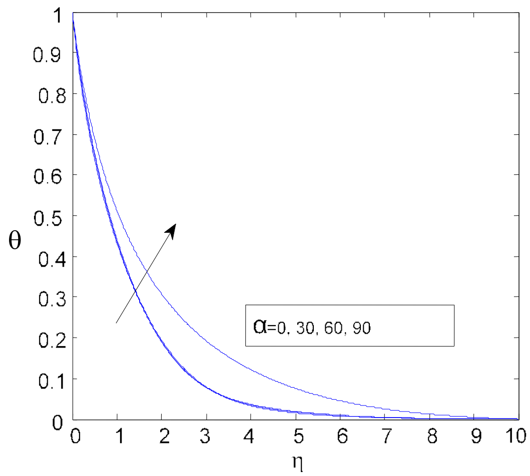

Figure 1(c) effects of α on temperature profile

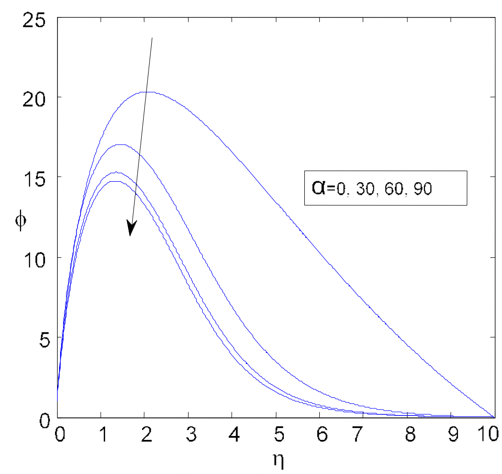

Figure 1(d) effects of α on nanofluid particle volume fraction profile

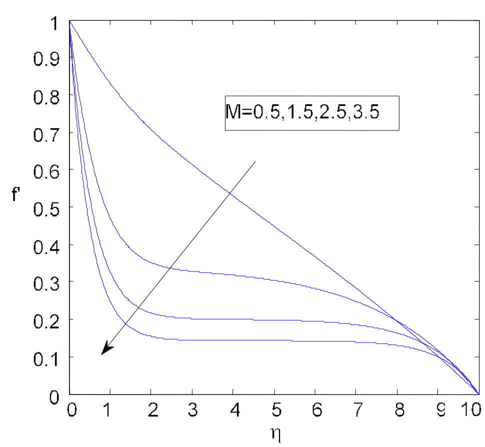

Figure 2(a) effects of magnetic parameter on velocity profile

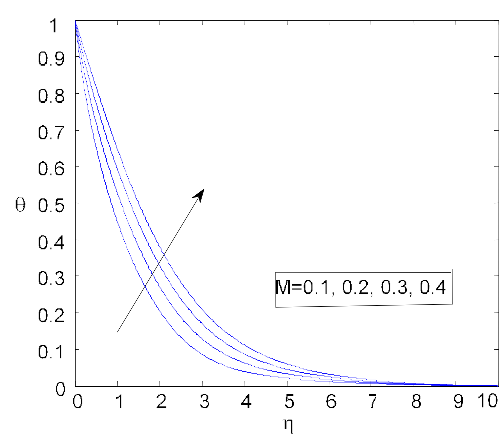

Figure 2(b) effects of magnetic parameter on temperature profile

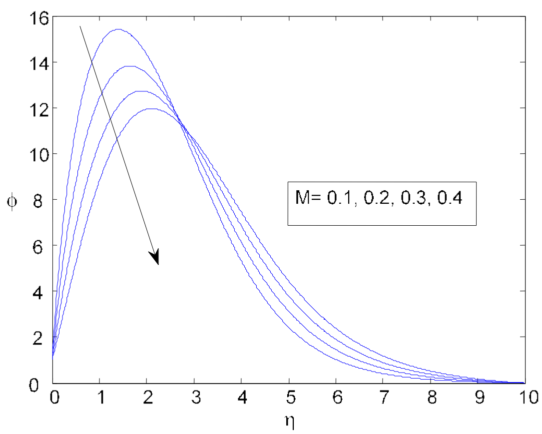

Figure 2(c) effects of magnetic parameter on nano particle volume fraction profile profile

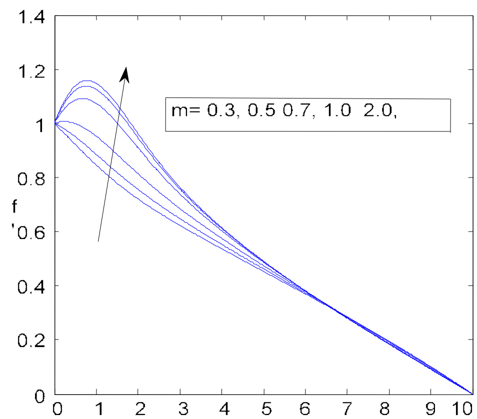

Figure 3(a) Effects of Hall parameter on velocity profile

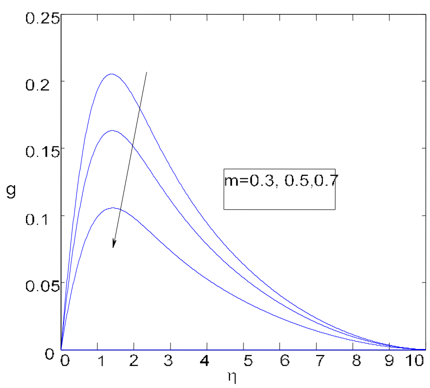

Figure 3(b) effects of Hall parameter on micropolar fluid

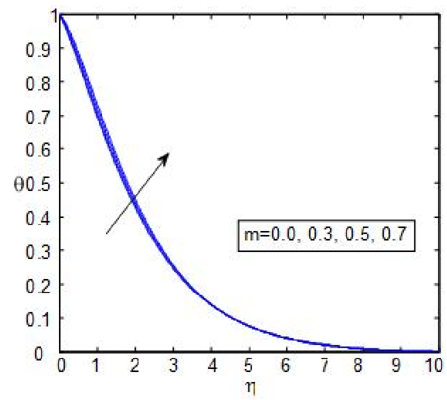

Figure 3(c) effects of Hall parameter on temperature profile

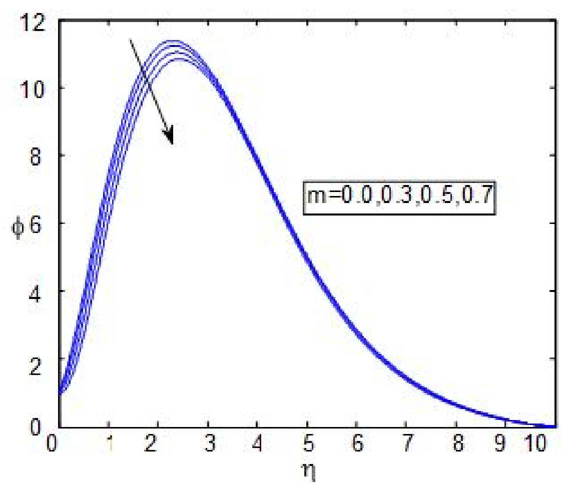

Figure 3(d) effects of Hall parameter on nano particle volume fraction profile

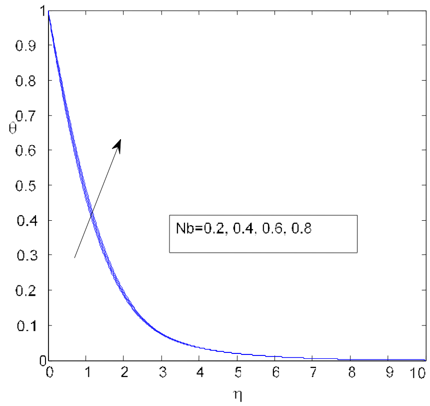

Figure 4(a) effects of Brownian motion parameter on temperature profile

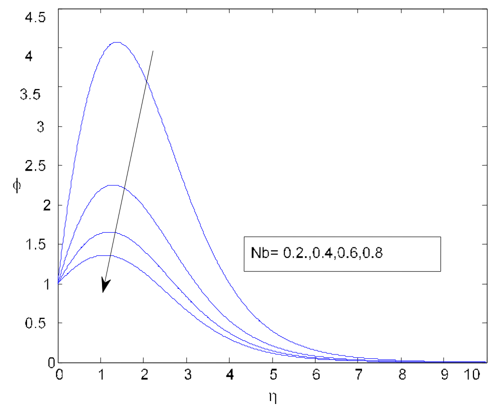

Figure 4(b) effects of Brownian motion parameter on nano particle volume fraction profile

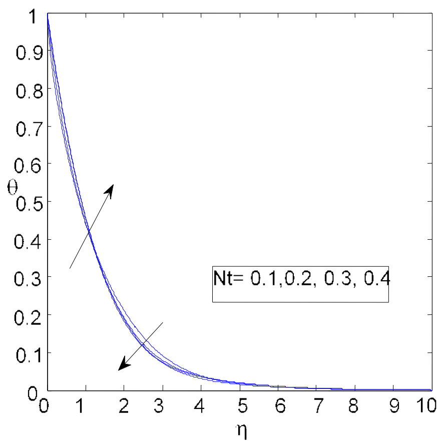

Figure 5(a) effects of thermophoresis parameter on temperature profile

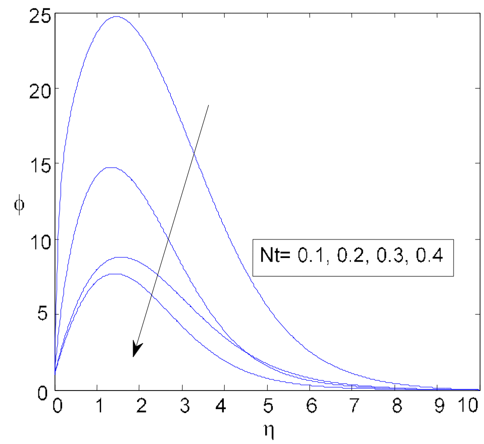

Figure 5(b) effects of thermophoresis parameter on nanoparticle volume fraction profile

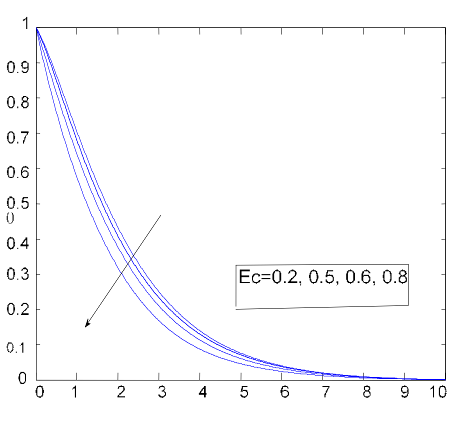

Figure 6(a) effects of Eckert number on temperature

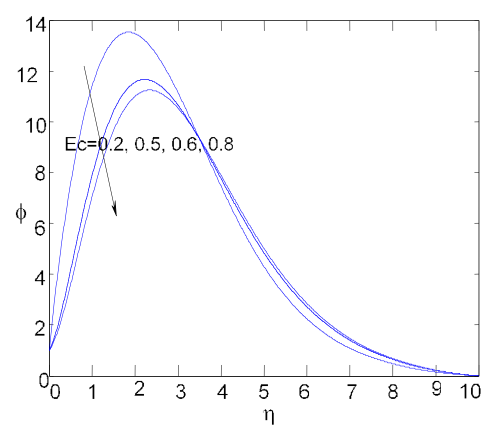

Figure 6(b) effects of Eckert number of nano particle volume fraction profile

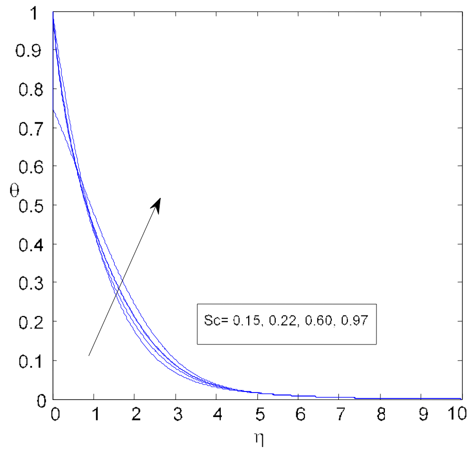

Figure 7(a) effects of Schmidts number on temperature profile

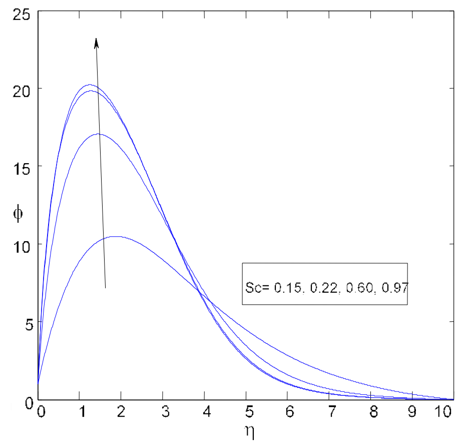

Figure 7(b) effects of Schmidts number on nano particlevolume fraction profile

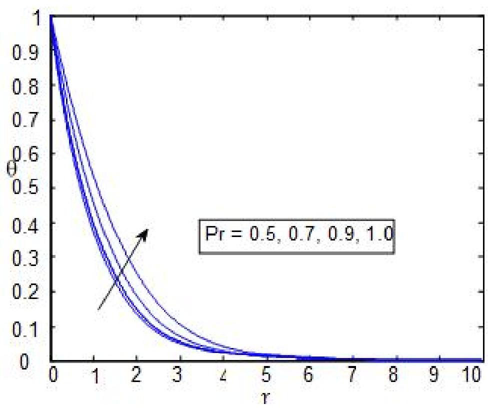

Figure 8(a) effects of Prandtl number on temperature profile

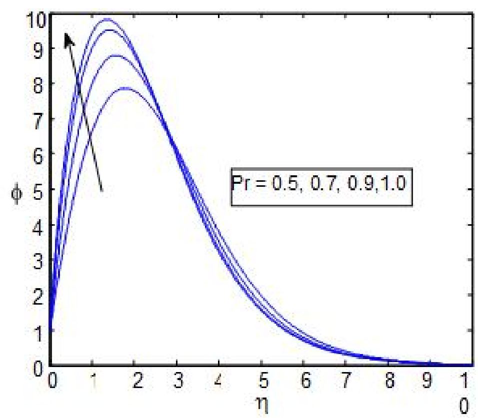

Figure 8(b) effects of Prandtl number on nano particle volume fraction profile

4 Conclusions

We have investigated the heat and mass transfer of MHD free convection of nanofluid with viscous dissipation and Hall current effects. The effects of different flow parameters on velocity, micropolar, temperature and nano particle volume fractions are examined and following conclusions have drawn:

- With the increasing of angle of inclination the velocity, micropolar fluid and nano particle volume fraction profiles are decreasing and the temperature is increasing.
- With the increasing magnetic parameter the velocity and nano particle volume fraction profile are decreasing. But the temperature profile.
- With the increase of Hall current parameter the velocity and temperature are increasing but the micropolar fluid motion and nano particle volume fraction profiles are decreasing.
- With an increasing of Brownian motion parameter the temperature profile is increasing and the nano particle

volume fraction profile is decreasing.

- with the increasing of thermophoresis parameter the temperature profile is increasing. But the nano particle volume fraction profile is decreasing.
- The temperature profile and the nano particle volume fraction profiles are decreasing with an increase of Eckert number.
- The temperature profile and the nano particle volume fraction profile are increasing with the increasing of Schmidt number.
- With an increase of Prandtl number the temperature profile and nano particle volume fraction profile is increasing.

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