Unsteady MHD mixed convection flow of a viscous dissipating micropolar fluids in a boundary layer slip flow regime with Joule heating

A. A. Bakr[a,b•], Z. A. S. Raizah[b]

a Department of Mathematics, Faculty of Science, Al-Azhar University, Assiut, Egypt. b Department of Mathematics, Faculty of Science. Abha, King Khaled University, Saudi Arabia

Abstract— Simultaneous heat and mass transfer in unsteady free convection flow with thermal radiation and thermal diffusion past an impulsively started infinite vertical porous plate subjected to a strong magnetic field is presented. The dimensionless governing equations for this investigation are solved analytically using two terms harmonic and non-harmonic functions. The influence of various parameters on the convectively cooled or convectively heated plate in the laminar boundary layer are established. An analysis of the effects of the parameters on the concentration, velocity and temperature profiles, as well as skin friction and the rates of mass and heat transfer is done with the aid of graphs and tables.

Keywords: Heat and mass transfer; Hall effects; Chemical reaction; Heat generation; Thermal diffusion; Thermal radiation;micropolar fluid.

1 Introduction

The study of flow and heat transfer for an electrically conducting micropolar fluid over a porous plate under the influence of a magnetic field has attracted the interest of many investigators in view of its applications in many engineering problems such as magnetohydrodynamic (MHD) generator, plasma studies, nuclear reactors, oil exploration and geothermal energy extractions [1]. In addition, due to its practical application to boundary layer control and thermal protection in high energy flow by means of wall velocity and mass transfer, considerable attention has been paid to the thermal boundary layer flows over moving boundaries[2]. The theory of micropolar fluids which takes into account the inertial characteristics of the substructure particles which are allowed to undergo rotation has been proposed by Eringen [3]. Micropolar fluids are fluids with microstructure belonging to a class of fluids with non-symmetrical stress tensor. Physically, they represent fluids consisting of randomly oriented particles suspended in a viscous medium.

It is well known that the boundary condition for a viscous fluid at a solid wall obeys no-slip condition, i.e., the fluid velocity matches the velocity of the solid boundary. However, in many practical applications, the particle adjacent to a permeable surface no longer takes the velocity of the surface but the particle at the surface has a finite tangential velocity which slips along the surface. The flow regime is called a slip-flow regime, and this effect cannot be neglected. Sharma and Chaudhury [4] studied the effect of variable suction on transient free convective viscous incompressible flow past a vertical plate in a slip-flow regime. Hayat et al. [5] investigated the flow of an elastico-viscous fluid past an infinite wall with time-dependent suction. Hayat et al [6] examined the non-Newtonian flows over an oscillating plate with variable suction. Sahin [7] have studied the influence of chemical reaction on transient MHD free convection flow over a vertical plate in slip-flow regime. Hayat et al [8] studied fluctuating flow of a third-order fluid past an infinite plate with variable suction. Sharma [9] investigated the effects of periodic temperature and concentration on the unsteady free stream consisting of a mean velocity which vary exponentially with time.

Many practical diffusive operations involve the molecular diffusion of species in the presence of a chemical reaction within or at the boundary layer. The study of heat and mass transfer in the presence of chemical reaction is of practical importance due to its occurrence in many branches of science and engineering. Chemical reaction usually accompany a large amount of exothermic and endothermic reactions. Thus the study of heat generation effects is important in moving fluids undergoing exothermic or endothermic chemical reaction. Muthucumaraswamy and Ganesan [10] studied the effect of first-order chemical reaction and injection flow on characteristics in an unsteady upward motion of an isothermal plate. Chamkha [11] studied the MHD flow of uniformly stretched vertical permeable surface in the presence of heat generation/absorption and a chemical reaction. Raptis and Perdikis [12] analyzed the effect of a chemical reaction of an electrically conducting viscous fluid on the flow over a non-linear (quadratic) semi-infinite stretching sheet in the presence of transverse magnetic field. Ibrahim et al. [13] studied the effect of the chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi-infinite vertical

•The corresponding author Tel.: +966 –0533879159; fax: 002-088-2325436
Email: aa_bakr2008@yahoo.com

permeable moving plate with heat source and suction. Ghaly and Seddeek [14] have investigated the effect of chemical reaction, heat and mass transfer on laminar flow among a semi infinite horizontal plate with temperature dependent viscosity. Bakr [15] has investigated free convection heat and mass transfer adjacent to moving vertical porous infinite plate for incompressible, micropolar fluid in a rotating frame of reference in the presence of heat generation or absorption effects, a first-order chemical reactions. Pal and Talukdar [16] studied effect of buoyancy and chemical reaction on MHD mixed convection heat and mass transfer in a porous medium with thermal radiation and Ohmic heating.

The objective of the present study is to analyze the effects of first-order chemical reaction and thermal radiation on Mixed convective flow of a micropolar fluid past an infinite vertical plate in the presence of viscous and Ohmic heating. We have also considered the slip velocity with periodic temperature and concentration boundary conditions at the plate surface in the present paper. Possible new emerging engineering areas of the type of the problem considered in the present paper can be found in many industries such as in powder industry and in generating electric power in which electrical energy is extracted directly from moving electrically conducting fluid. Also, the results would be useful in many practical areas related to the diffusive operations which involve the molecular diffusion of species with chemical reaction. The flow in the porous medium deals with the analysis in which the differential equations governing the motion is based on Darcy's law, which accounts for the drag exerted by the porous medium. The classical model introduced by Cogley et al. [17] is used for the radiation effects as it has the merit of simplicity and enables us to introduce linear term in temperature in the analysis for optically thin media.

2 MATHEMATICAL ANALYSIS

Consider unsteady MHD mixed convection flow of a micropolar fluid from a permeable semi-infinite verticalplate subject to slip boundary condition at the interface of porous medium in the presence of thermal radiation, viscous and Joule heating effects. Time dependent suction velocity is imposed on the plate surface. A uniform transverse magnetic field of magnitude B0 is applied in the direction of y*-axis in the presence of thermal radiation and thermal and concentration buoyancy effects. The x* -axis is taken along the vertical infinite plate, which is the direction of the flow and y*-axis is taken normal to the plate (see Fig. 1). We assume that no electric field is present and induced magnetic fields are negligible. The porous medium is assumed to be uniform, isotropic and in thermal equilibrium with the plate. The plate is having variable temperature and concentration which varies with time. All fluid properties are assumed to be constant except the density in the body force term of the linear momentum balance. Under the Boussinesq and boundary layer approximations the governing equations for this problem can be written as

$$\frac{\partial v^*}{\partial y^*} = 0, \tag{1}$$

$$\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial P}{\partial x^*} + (\upsilon + \upsilon_r)\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta_T (T^* - T_\infty) + g\beta_C (C^* - C_\infty) - \left(\frac{\sigma B_0^2}{\rho} + \frac{\nu}{K^*}\right)u^* + 2\upsilon_r \frac{\partial \omega^*}{\partial y^*} \tag{2}$$

$$\frac{\partial \omega^*}{\partial t^*} + v^* \frac{\partial \omega^*}{\partial y^*} = \frac{\gamma^*}{\rho j^*}\frac{\partial^2 \omega^*}{\partial y^{*2}} \tag{3}$$

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \alpha \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{Q}{\rho C_p}(T - T_\infty) + \frac{\nu}{C_p}\left(\frac{\partial u^*}{\partial y^*}\right)^2 + \left(\frac{\sigma B_0^2}{\rho C_p} + \frac{\nu}{C_p K^*}\right) u^{*2} - \frac{1}{\rho C_p}\frac{\partial q_r^*}{\partial y^*} \tag{4}$$

$$\frac{\partial C^*}{\partial t^*} + w^* \frac{\partial C^*}{\partial z^*} = D_m \frac{\partial^2 C^*}{\partial z^{*2}} - R(C^* - C_\infty) \tag{5}$$

where u^*, v^* *and* t^* are the dimensional distances along and perpendicular to the plate and dimensional time, respectively, u^* *and* v^* are the components of dimensional velocities along x^* *and* y^* directions, respectively, T is the dimensional temperature, C^* is the dimensional concentration, C_w and T_w are the concentration and temperature at the wall, respectively. C_∞ and T_∞ are the free stream dimensional concentration and temperature, respectively. ρ is the fluid density, ν is the kinematic viscosity, C_p is the specific heat at constant pressure, Bo is the magnetic induction, K^* is the permeability of the porous medium, B_T and B_c are the thermal and concentration expansions coefficients, respectively, Q is the dimensional heat absorption coefficient, D is the mass diffusivity, g is the gravitational acceleration, R is the chemical reaction parameter, q_r^* is the local radiative heat flux. The term $Q(T - T_\infty)$ is assumed to be the amount of heat generated or absorbed per unit volume, Q is a constant, which may take on either positive or negative values. When the wall temperature T^* exceeds the free stream temperature T_∞, the source term $Q > 0$ and heat sink when $Q < 0$. The second and third terms on RHS of the momentum Eq. (2) denote the thermal and concentration buoyancy effects, respectively. Also, the fourth and fifth terms on the RHS of energy Eq. (4) represents the viscous and Joule heating effects, respectively. The second and third term on the RHS of Eq. (4) denote the inclusion of the effect of heat absorption and thermal radiation effects, respectively. The boundary conditions for the model are:

$$u^* = U_0 + L_1^* \frac{\partial u^*}{\partial y^*}, \quad \omega^* = -m\frac{\partial u^*}{\partial y^*}, T = T_w + \varepsilon(T_w - T_\infty)e^{n^* t^*}, C^* = C_w + \varepsilon(C_w - C_\infty)e^{n^* t^*} \quad at\ y^*$$
$$u^* \to U_\infty^* = U_0(1 + \varepsilon e^{n^* t^*}), \omega^* \to 0, T^* \to T_\infty, C^* \to C_\infty \quad as\ y^* \to \infty \tag{6}$$

The boundary condition for microrotation variable ω^* describes its relationship with the surface stress. In the above boundary condition (6), the parameter m is a number between 0 and 1 that relates to the microgyration vector to the shear stress. It is noteworthy that for the case m = 0 and from the boundary condition stated above we have $\omega^*(0)=0$, this corresponds to the case where the particle density is sufficiently large so that microelements close to the wall are unable to rotate. The case corresponding to $m = 0.5$ results in the vanishing of the antisymmetric part of the stress tensor and represents weak concentration. The value $m = 1$ is representative of turbulent boundary layer. In the above boundary condition (6) the plate is in uniform motion and subjected to variable suction and slip boundary condition. In the parameter $L_1^* = \frac{2-m_1}{m_1}L$, L is the molecular mean free path and m_1 is the tangential momentum accommodation coefficient. Boundary conditions (6) is based on the slip-flow condition with oscillatory temperature and concentration prevailing at the permeable surface. The radiative heat flux is given by [17] as

$$\frac{\partial q_r^*}{\partial y^*} - = 4(T - T_\infty)I' \tag{7}$$

where $I' = \int_0^\infty K_{\lambda w}\frac{\partial e_{b\lambda}}{\partial T^*}d\lambda$, $K_{\lambda w}$ is the absorption coefficient at the wall and $e_{b\lambda}$ is Plank's function. The advantages and limitations of the Cogley-Vincenti-Giles formulation, which is to used to simulate the radiation component of heat transfer, are (i) it does not require an extra transport equation for the incident radiation, and (ii) it can only be used for an optically thin, near-equilibrium and non-gray gas. Cogley model is well suited for (i) surface-to-surface radiant heating or cooling, (iii) Coupled radiation, convection, and/or conduction heat transfer and (iv) Radiation in glass processing, glass fiber drawing, and ceramic processing.

The suction velocity is assumed to take the following exponential form:

$$v^* = -V_0(1+\varepsilon A e^{n^* t^*}) \tag{8}$$

where A is real positive constant, ε is constant $(A<1)$ and V_0 is a scale of suction velocity which has non-zero positive constant. Outside the boundary layer, Eq.(2) gives

$$-\frac{1}{\rho}\frac{\partial P}{\partial x^*} = \left(\frac{\sigma B_0^2}{\rho} + \frac{\nu}{K^*}\right)U_\infty^* + \frac{\partial U_\infty^*}{\partial t^*} \tag{9}$$

Proceeding with analysis, we introduce the following dimensionless variables:

$$y = \frac{y^* V_0}{\upsilon},\ u = \frac{u^*}{U_0},\ v = \frac{v^*}{V_0},\ t = \frac{t^* V_0^2}{\upsilon},\ n = \frac{n^*\upsilon}{V_0^2},\ \omega = \frac{\upsilon\omega^*}{U_0 V_0},$$
$$\theta = \frac{T - T_\infty}{T_w - T_\infty},\ C(z,t) = \frac{C^* - C_\infty}{C_w - C_\infty},\ U_\infty = \frac{U_\infty^*}{U_0} \tag{10}$$

In view of Eqs. (7)-(10), the governing Eqs. (1)-(6) reduce to the following dimensionless form:

$$\frac{\partial u}{\partial t} - (1+\varepsilon A e^{nt})\frac{\partial u}{\partial y} = \frac{dU_\infty}{dt} + (1+\Delta)\frac{\partial^2 u}{\partial y^2} + Gr\,\theta + GmC$$
$$+ \left(M + \frac{1}{K}\right)(U_\infty - u) + 2\Delta\frac{\partial\omega}{\partial y} \tag{11}$$

$$\frac{\partial\omega}{\partial t} - (1+\varepsilon A e^{nt})\frac{\partial\omega}{\partial y} = \frac{1}{\lambda}\frac{\partial^2\omega}{\partial y^2} \tag{12}$$

$$\frac{\partial\theta}{\partial t} - (1+\varepsilon A e^{nt})\frac{\partial\theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2} - (F+\phi)\theta + NEcu^2 + Ec\left(\frac{\partial u}{\partial y}\right)^2 \tag{13}$$

$$\frac{\partial C}{\partial t} - (1+\varepsilon A e^{nt})\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - \gamma C \tag{14}$$

The boundary conditions are

$$u = 1 + h\frac{\partial u}{\partial y},\ \omega = -m\frac{\partial u}{\partial y},\ \theta = 1+\varepsilon e^{nt}, C = 1+\varepsilon e^{nt},\ on\ \ y = 0$$
$$u = U_\infty \to (\theta = 1+\varepsilon e^{nt}), \omega\to 0, \theta\to 0, C\to 0, \quad as\ \ y\to\infty \tag{15}$$

where Gr and Gm are the Grashof and solutal Grashof number, Pr is the Prandtl number, M is the magnetic field parameter, K is the permeability parameter, γ is the Chemical reaction parameter, Sc is the Schmidt number, ϕ is the heat source parameter and F is the absorption of radiation parameter.

$$Sc = \frac{\upsilon}{D_m}, \Pr = \frac{\upsilon\rho c_p}{k}, Gr = \frac{g\beta_T(T_w - T_\infty)}{V_0^2 U_0},\ \ Gm = \frac{g_0\beta_C(C_w - C_\infty)\upsilon}{V_0^2 U_0},$$
$$\phi = \frac{Q\upsilon}{\rho C_p V_0^2}, F = \frac{4\upsilon I'}{\rho C_p V_0^2}, M = \frac{\sigma B_0^2\upsilon}{\rho V_0^2}, \Delta = \frac{K}{\rho\upsilon}, \lambda = \frac{\gamma^*}{\mu j^*} = (1+\frac{1}{2}\Delta),$$
$$Ec = \frac{U_0^2}{C_p(T_w - T_\infty)},\ \ h = \frac{L_1^* V_0}{\nu},\ \ \gamma = \frac{R\upsilon}{V_0^2},\ N = M + \frac{1}{K}$$

Furthermore, the spin-gradient viscosity which gives some relationship between the coefficient of viscosity and micro-inertia is defined as $\gamma^* = (\mu + \frac{\Lambda}{2})j^* = \mu(1+\frac{\Delta}{2})j^*$ where Δ denotes the dimensionless viscosity ratio, defined as follows: $\Delta = \frac{\Lambda}{\mu}$ in which Λ is the coefficient of gyro-viscosity (or vortex viscosity). The mathematical statement of the problem is now complete and embodies the solution of Equations (11)-(14) subject to boundary conditions (15)

3 Solution

In order to reduce the above system of partial differential equations to a system of ordinary differential equations in dimensionless form, we perform an asymptotic analysis by representing the linear velocity, microrotation temperature and concentration as

$$Q(y,t) = Q_0(y) + \varepsilon e^{nt}Q_1(y) + O(\varepsilon^2) \tag{16}$$

where Q are u, ω, θ, C, By substituting the above Eqs.(16) into Eqs.(11-15), equating the harmonic and non-harmonic terms, and neglecting the higher order of $O(\varepsilon^2)$, and simplifying we obtains the following pairs of equations for $u_0, \omega_0, \theta_0, C_0$ and $u_1, \omega_1, \theta_1, C_1$:

$$(1+\Delta)u_0'' + u_0' - Nu_0 = -N - Gr\theta_0 + GmC_0 - 2\Delta\omega_0', \tag{17}$$

$$(1+\Delta)u_1'' + u_1' - (N+n)u_1 = -(N+n) - Au_0' - Gr\theta_1 + GmC_1 - 2\Delta\omega_1', \tag{18}$$

$$\omega_0'' + \lambda\,\omega_0' = 0, \tag{19}$$

$$\omega_1'' + \lambda\,\omega_1' - \lambda\,\omega_1 = -\lambda A\omega_0', \tag{20}$$

$$\theta_0'' + \Pr\theta_0' - \Pr(F+\phi)\theta_0 = -\Pr N\,Ecu_0^2 - -\Pr\,Ecu_0'^2, \tag{21}$$

$$\theta_1'' + \Pr\theta_1' - \Pr(F + \phi + n)\theta_1 = -2\Pr N\,Ec u_0\, u_1 - 2\Pr\, Ec u_0' u_1' - A\Pr\theta_1', \quad (22)$$

$$C_0'' + ScC_0' - Sc\gamma\, C_0 = 0, \quad (23)$$

$$C_1'' + ScC_1' - Sc(\gamma + n)C_1 = -AScC_0', \quad (24)$$

subject to the boundary conditions

$$u_0 = 1 + hu_0',\ u_1 = hu_1',\ \omega_0 = -mu_0',\ \omega_1 = -mu_1',\ \theta_0 = \phi_0 = \theta_1 = \phi_1 = 1 \ at\ y = 0$$
$$u_0 \to 1,\quad u_1 \to 1,\ \omega_0 \to 0,\ \omega_0 \to 0,\ \theta_0 \to 0\ \ \theta_0 \to 0,\ \phi_0 \to 0,\ \phi_0 \to 0\ \ as\ \ y \to \infty \quad (25)$$

Eqs. (17)-(24) are still coupled, but a great deal of insight into the behavior of the flow variables can be obtained if we seek an asymptotic series solution about the Eckert number Ec , which for most incompressible flows is small. We therefore expand our flow variables as

$$Q_0(y) = Q_{01}(y) + EcQ_{02}(y) + O(Ec^2) \quad (26)$$

where Q are u, ω, θ, C , Substitution of Eq. (26) into Eqs. (17)-(24) and equating to zero the coefficient of different powers of Ec and neglecting higher order terms in Ec , we obtained the following sequence of approximations

$$(1+\Delta)u_{01}'' + u_{01}' - N u_{01} = -N - Gr\theta_{01} + GmC_{01} - 2\Delta\,\omega_{01}', \quad (27)$$

$$(1+\Delta)u_{02}'' + u_{02}' - N u_{02} = -Gr\theta_{02} + GmC_{02} - 2\Delta\,\omega_{02}', \quad (28)$$

$$(1+\Delta)u_{11}'' + u_{11}' - (N+n)u_{11} = -(N+n) - Au_{01}' - Gr\theta_{11} + GmC_{11} - 2\Delta\,\omega_{11}', \quad (29)$$

$$(1+\Delta)u_{12}'' + u_{12}' - (N+n)u_{12} = -(N+n) - Au_{02}' - Gr\theta_{12} + GmC_{12} - 2\Delta\,\omega_{12}', \quad (30)$$

$$\omega_{01}'' + \lambda\,\omega_{01}' = 0, \quad (31)$$

$$\omega_{02}'' + \lambda\,\omega_{02}' = 0, \quad (32)$$

$$\omega_{11}'' + \lambda\,\omega_{11}' - \lambda\,\omega_{11} = -\lambda A\omega_{01}', \quad (33)$$

$$\omega_{12}'' + \lambda\,\omega_{12}' - \lambda\,\omega_{12} = -\lambda A\omega_{02}', \quad (34)$$

$$\theta_{01}'' + \Pr\theta_{01}' - \Pr(F+\phi)\theta_{01} = 0, \quad (35)$$

$$\theta_{02}'' + \Pr\theta_{02}' - \Pr(F+\phi)\theta_{02} = -\Pr N u_{01}^2 - -\Pr u_{01}'^2, \quad (36)$$

$$\theta_{11}'' + \Pr\theta_{11}' - \Pr(F+\phi+n)\theta_{11} = -A\Pr\theta_{01}', \quad (37)$$

$$\theta_{12}'' + \Pr\theta_{12}' - \Pr(F+\phi+n)\theta_{12} = -2\Pr N u_{01}u_{11} - 2\Pr\, Ecu_{01}'u_{11}' - A\Pr\theta_{02}', \quad (38)$$

$$C_{01}'' + ScC_{01}' - Sc\gamma\, C_{01} = 0, \quad (39)$$

$$C_{02}'' + ScC_{02}' - Sc\gamma\, C_{02} = 0, \quad (40)$$

$$C_{11}'' + ScC_{11}' - Sc(\gamma+n)C_{11} = -AScC_{01}', \quad (41)$$

$$C_{12}'' + ScC_{12}' - Sc(\gamma+n)C_{12} = -AScC_{02}', \quad (42)$$

$$u_{01} = 1 + hu_{01}', u_{02} = hu_{02}', u_{11} = hu_{11}', u_{12} = hu_{12}', \omega_{01} = -mu_{01}'$$
$$, \omega_{02} = -mu_{02}', \omega_{11} = -mu_{11}', \omega_{12} = -mu_{12}', \quad \theta_{01} = C_{01} = \theta_{11} =$$
$$C_{11} = 1, \theta_{02} = C_{02} = \theta_{12} = C_{12} = 0 \qquad at \qquad y = 0 \quad (43)$$
$$u_{01} = u_{11} \to 1,\ u_{02} = u_{12} = \omega_{01} = \omega_{02} = \omega_{11} = \omega_{12} \to 0$$
$$\theta_{01} = \theta_{02} = \theta_{11} = \theta_{12} = C_{01} = C_{02} = C_{11} = C_{12} \to 0 \ \ as \ \ y \to \infty$$

The Eqs. (27)-(42) satisfying boundary conditions (43) are solved analytically.

The physical quantities of interest are which the local wall shear stress τ_w. Given the velocity field in the boundary layer, we can now calculate the local wall shear stress (i.e., skin-friction) is given by

$$\tau_w = \left[\mu\frac{\partial u}{\partial y^*}\right]_{y^*=0} = \rho\, UV_0 u'(0), \quad (48)$$

therefore, the local friction factor C_f is given by $C_f = \dfrac{\tau_w}{\rho U V_0} = u'(0)$. In addition, the rate of heat transfer at the surface of wall in terms of Nusselt number Nu, can be written as:

$$\mathrm{Nu} = x\frac{(\partial T/\partial y)}{T_\infty - T_w}\bigg|_{y=0} \quad ; Nu = -\mathrm{Re}_x\,\theta'(0) \quad (49)$$

4 Results and discussion

The non-linear coupled Eqs. (27)-(42) subject to boundary conditions (43), which describe heat and mass transfer flow past an infinite vertical plate immersed in a porous medium in the presence of thermal radiation, viscous and Joule heating under the influence of magnetic field are solved analytically by perturbation technique. In order to get physical insight into the problem, the effects of various parameters encountered in the equations of the problem are analyzed on velocity, temperature and concentration fields with the help of figures. These results show the influence of the various physical parameters such as thermal Grashof number Gr, solutal Grashof number Gc , magnetic field parameter M, Schmidt number Sc, permeability parameter K, heat absorption parameter , chemical reaction parameter and thermal radiation parameter F on the velocity, temperature and the concentration profiles. We have also analyzed the effects of various

physical parameters such as magnetic field, thermal radiation, viscous and Joule heating on skin friction coefficient, local Nusselt number and local Sherwood number. We can extract interesting insights regarding the influence of all the parameters that govern this problem. In Figs. 2-7 we have prepared some graphs of the velocity, microrotation and temperature profiles for micropolar fluids with the fixed flow conditions and material parameters. The effect of viscosity ratio Δ on the velocity and angular velocity for a stationary porous plate is presented in Figs. 2. From these figures it is shown that increase viscosity ratio results in increasing the velocity. Furthermore, the angular velocity distributions decreases as Δ parameter increases. The influences of the chemical reaction parameter on the velocity profiles across the boundary layer are presented in Fig. 3. We see that the velocity distribution across the boundary layer increases with deceasing of γ. For different values of the chemical reaction parameter γ, the angular velocity profiles is obvious that the influence of increasing values of γ. Also, shows the variation of temperature and concentration profiles for different value of γ. It is seen from this figure the temperature and concentration profiles increase with decreasing of chemical reaction parameter γ. Fig. 4 is a plot of velocity profiles for various values of rarefaction parameter h. It is evident from this figure that velocity distribution increases near the plate and then decreases exponentially far away from the plate till it attains the minimum values as $y \to \infty$. The effect of increasing the values of rarefaction parameter is to increase the velocity in the momentum boundary layer with formation of sharp peak near the plate. Thus the effect of h is more prominently observed very close to the plate which ultimately vanished far away from the plate. Also,the angular velocity distributions increases as h parameter increases. The effects of radiation parameter F on velocity profiles are presented in Fig. 5. From this figure we observe that, as the value of F increases, the velocity profiles decreases in the momentum boundary layer due to the fact that the momentum boundary layer thickness decreases with increase in the radiation parameter F . Fig. 7 shows the variation of temperature profiles with y for thermal radiation parameter F . It is noted that the increase in the radiation parameter F results in decrease in the value of the temperature in the thermal boundary layer due to the fact that, the divergence of radiation heat flux $\frac{\partial q_r}{\partial y}$ decreases as the absorption coefficient $K_{\lambda w}$ at the wall increases which in turn decreases the rate of radiative heat transfer to the fluid which causes the fluid temperature to decrease.

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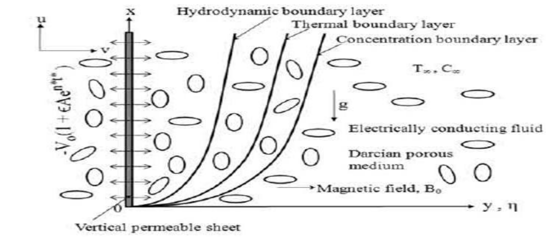


Fig. 1. Physical configuration of the problem.

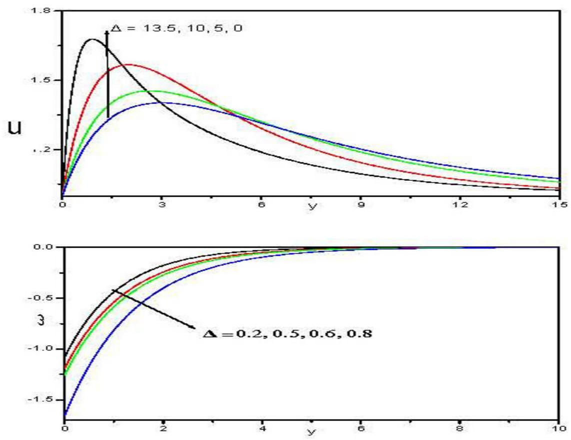
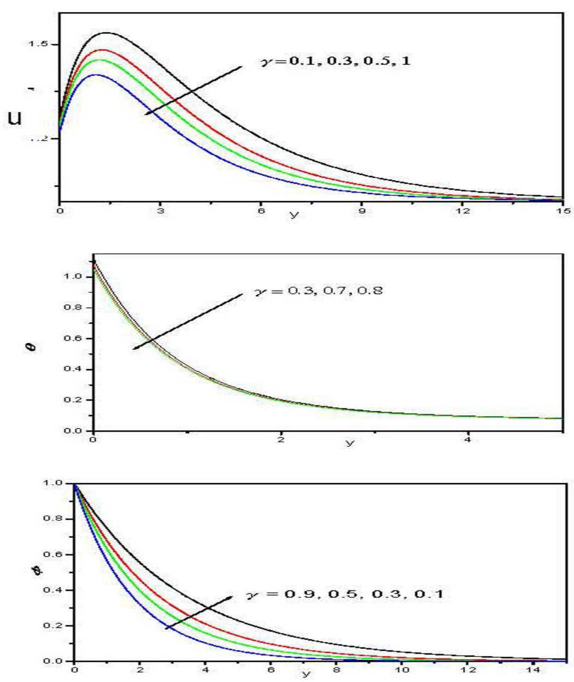


Figure 2 : Effect of Δ on velocity and microrotation profiles for Gr=2, Gm=2, Pr=0.71, M=0.5, γ=0.1, K=0.5, F=0.5, A=0.5, Sc=0.16, m=0.5, h=0 and φ=0.3 .



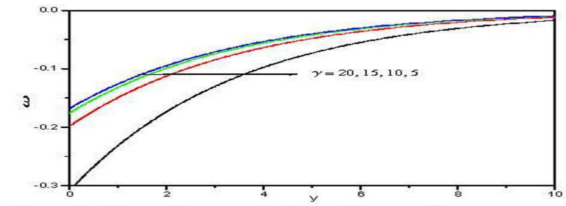


Figure 3: Effect of γ on velocity , microrotation, Temperature and Concentration profiles for Gr=2, Gm=2, Pr=0.71, M=0.5,Sc=0.22, K=0.5, F=0.5, A=0.5, h=0.5, m=0.5 , Δ=5 and φ=0.3

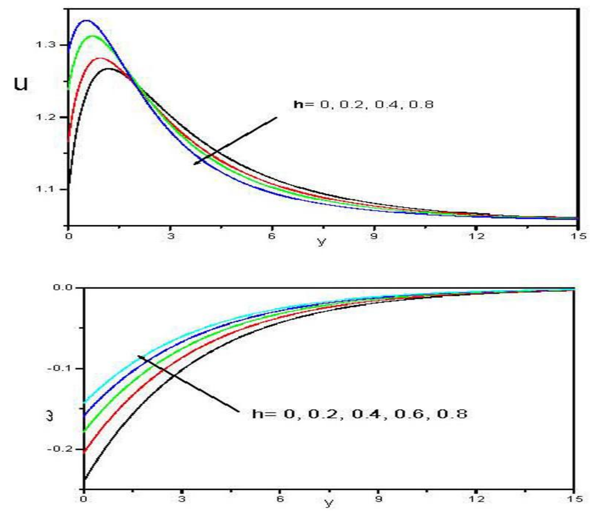


Figure 4: Effect of *h* on velocity, microrotation , Temperature and Concentration profiles for Gr=2, Gm=2, Pr=0.71, M=0.5, γ=20, K=0.5, F=0.5, A=0.5, Sc=0.22, m=0.5, Δ=5 and φ=0.3 .

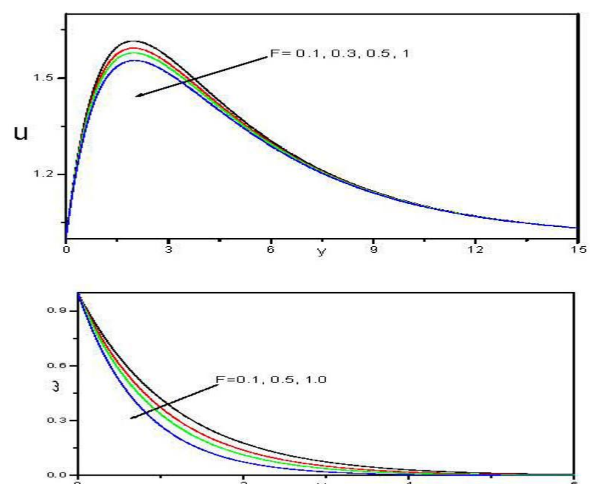


Figure 5: Effect of F on velocity, microrotation and Temperature profiles for Gr=2, Gm=2, Pr=0.71, M=0.5, γ=0.1, K=0.5, φ=0.1, A=0.5, Sc=0.16, m=0.5, h=0 and Δ=5 .