Micropolar Fluid Behavior with Constant Pressure, Permeability, Heat and Mass Transfer

Asibor Raphael Ehikhuemhen, Omokhuale Emmanuel

Abstract: ***Micropolar fluid behavior on convective boundary layer flow with constant pressure, permeability, heat and mass transfer have been studied analytically. Perturbation technique is used as the main tool for the analytic approach. Some non-dimensional quantities are used to transform the governing equations. The non-dimensional equations for the momentum, angular momentum, temperature and concentration are solved analytically to obtain approximate solutions by the above mentioned technique. With the aid of graphs, the effects of various important parameters associated with the velocity, micro rotation, temperature and concentration fields within the boundary layer were examined and discussed. Further, the skin friction coefficients at the plate was computed and the influence of physical parameters of engineering interest were discussed.***

Index Terms: ***Mass transfer, Micropolar fluid, Magneto-hydrodynamic, Porous medium***

I. INTRODUCTION

The theory of micropolar fluids is generating a very much-increased interest and many classical flows are being re-examined to determine the effect of the fluid microstructure Sultana *et al.* (2011). The dynamics of micropolar fluids, originated from the theory of Eringan (1966) has been a popular area of research by many scholars. Micropolar fluids are those, which contain micro-constituents that can undergo rotation, the presence of which can affect the hydrodynamics of the flow so that it can be distinctly non-Newtonian. It has many practical applications. For example analyzing the behavior of exotic lubricants, the flow of polymic fluids, liquids crystals, additive suspensions, human and animal blood, turbulent shear flow and so forth. The concept of micropolar fluids deals with a class of fluids that exhibit microscopic effects arising from the local structure of motions of fluid elements. These fluids contain dilute suspension of rigid macromolecules with individual motions that support stress and body moments and are influenced by spin inertia. Islam *et al.* (2011) studied MHD micropolar fluid flow through vertical porous medium. Rahman and Sultana (2008) studied radiative heat transfer flow of micropolar fluid with variable heat flux. Abo-Eldahab and Ghonaim (2005) investigated radiation effect on heat transfer Khedr *et al.* (2009) examined MHD flow of a micropolar fluid past a stretched permeable surface with heat generation or absorption. Kim and Lee (2002) investigated the oscillatory flow of a micropolar fluid while Sharma and Gupta (1995) studied the effects of porous medium permeability and thermal convection in micropolar fluids. Hassanien and Gorla (1990) studied heat transfer to a micropolar fluid from a non-isothermal stretching sheet with suction and blowing. Kim (2001) investigated unsteady MHD micropolar flow and heat transfer over a vertical porous moving plate with variable suction.

El-Amin (2001) investigated MHD free convection and mass transfer flow in micropolar fluid with constant suction. Patil and Kulkarni (2008) examined effects in the presence of internal heat generation. Satya and Dubey (2011) investigated free convection flow with heat generation and thermal diffusion. Other authors who have contributed in this field are Haque *et al.* (2012); Olajuwon and Oahimire (2013); Aurangzaib et al. (2013); Ahmad et al. (2013) and Ashraf and Batool (2013). Recent works on Micropolar fluid behavior can be found in Nayok et al. (2015); Hussanan (2016) and Singh and Kumar (2016). Very recently, Reddy and Reddy (2017) presented micropolar fluid flow over a vertical surface in the presence of Cattaneo-Christov heat flux and viscous dissipation.

Motivated by the above studies and applications, the present paper studies micropolar fluid behavior with constant pressure, permeability, heat and mass transfer in a porous medium analytically to obtain approximate solutions for the momentum, angular momentum, temperature and concentration. This is to fill the gap existing in the literatures.

II. MATHEMATICAL FORMULATION

Consider the flow of unsteady flow of a laminar incompressible, micropolar fluid past a semi- infinite vertical porous moving plate embedded in a porous medium and subjected to a transverse magnetic field in the presence of heat and mass transfer and with Hall Effect and constant pressure. It is assumed that there is no applied voltage which implies the absence of an electric field. The transversely applied magnetic field and Reynolds number are very small and hence the induced magnetic field is negligible. Viscous and Darcy resistance terms are taken into account the constant permeability porous medium. It is also assumed here that the hole size of the porous plate is significantly larger than a characteristics microscopic length scale of porous medium.

The governing equations for the continuity, momentum, angular velocity, energy and concentration are as follows;

Manuscript published on 30 August 2017.
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$$\frac{\partial v^*}{\partial y^*}=0 \qquad (1)$$

$$\frac{\partial u'}{\partial y^*}+v^*\frac{\partial u'}{\partial y^*}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\left(\nu+\nu_r\right)\frac{\partial^2 u'}{\partial y^{*2}}+g\beta\left(T-T_\infty\right)+g\beta c\left(C-C_\infty\right)-\frac{\nu u'}{K^*}$$

$$-\frac{\sigma B_0\left(u'+m\omega^*\right)}{\rho(1+m^2)}+2\nu_r\frac{\partial \omega^*}{\partial y^*} \qquad (2)$$

$$\rho j\left(\frac{\partial \omega}{\partial t^*}+v^*\frac{\partial \omega}{\partial y^*}\right)=\gamma\frac{\partial^2 \omega}{\partial y^{*2}} \qquad (3)$$

$$\frac{\partial T'}{\partial t^*}+v^*\frac{\partial T'}{\partial y^*}=\alpha\frac{\partial^2 T'}{\partial y^{*2}} \qquad (4)$$

$$\frac{\partial C'}{\partial t^*}+v^*\frac{\partial C'}{\partial y^*}=D\frac{\partial^2 C'}{\partial y^{*2}} \qquad (5)$$

where $v=-v_0\left(1+\varepsilon A e^{in^* t^*}\right)$, x^* and y^* are the dimensional distances longitudinal and perpendicular to the plate, respectively. u^* and v^* are the components of the velocity in dimensional velocities along x^* and y^* directions, respectively. ρ is the density, ν is the kinematic viscosity, ν_r is the kinematic rational viscosity, g is the acceleration due to gravity, β and βc are the coefficients of volumetric thermal expansion of the fluid, K^* is the permeability of porous medium σ is the electrical conductivity of the fluid, B_0 is the magnetic induction, $j^*$is the micro inertia density, ω^* is the component of the angular velocity vector normal to the x, y- plane, γ is the spin gradient viscosity, T is the temperature and α is the effective fluid thermal diffusivity.

where $v_0>0$ and the negative sign indicate that the suction is towards the plane.

The boundary conditions of the problem are:

$$\left.\begin{array}{l} u^*=u_p^*, T=T_\omega+\varepsilon(T_\omega-T_\infty)e^{in^*t^*}, C=C_\omega+\varepsilon(C_\omega-C_\infty)e^{in^*t^*} \\ at\ y=0 \\ u^*\to u_\infty^*=U_\infty\left(1+\varepsilon e^{in^*t^*}\right), T\to T_\infty, C\to C_\infty, \omega^*\to 0 \\ as\ y\to\infty \end{array}\right\} \qquad (6)$$

Introducing the following non-dimensional variables

$$\left.\begin{array}{l} u=\dfrac{u'}{u_p}, v=\dfrac{v^*}{v_0}, y=\dfrac{y^* v_0}{\nu}, u_p=\dfrac{u_p^*}{u_0} \\ \omega=\dfrac{\nu}{u_0 v_0}\omega^*, t=\dfrac{t^* v_0^2}{\nu}, \theta=\dfrac{T-T_\infty}{T_\omega-T_\infty}, C=\dfrac{C-C_\infty}{C_\omega-C_\infty} \end{array}\right\} \qquad (7)$$

Substituting the dimensionless variable in (7) into (2), (3), (4) and (5), and also using (6). We get

$$\frac{\partial u}{\partial t}-(1+\varepsilon\lambda e^{int})\frac{\partial u}{\partial y}=B+(1+\beta)\frac{\partial^2 u}{\partial y^2}+Gr\theta+GcC-\frac{u}{K}$$
$$-\frac{Mu}{(1+m^2)}+2\beta\frac{\partial \omega}{\partial y} \qquad (8)$$

$$\frac{\partial \omega}{\partial t}-(1+\varepsilon\lambda e^{\mathrm{int}})\frac{\partial \omega}{\partial y}=\frac{1}{\eta}\frac{\partial^2 \omega}{\partial y^2} \qquad (9)$$

$$\frac{\partial \theta}{\partial t}-(1+\varepsilon\lambda e^{\mathrm{int}})\frac{\partial \theta}{\partial y}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} \qquad (10)$$

$$\frac{\partial C}{\partial t}-(1+\varepsilon\lambda e^{\mathrm{int}})\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \qquad (11)$$

With boundary conditions

$$\left.\begin{array}{l} u=u_p, \theta=1+\varepsilon e^{\mathrm{int}}, C=1+\varepsilon e^{\mathrm{int}}, \dfrac{\partial \omega}{\partial y}=-\dfrac{\partial^2 u}{\partial y^2}\ at\ y=0 \\ u\to U_\infty, \theta\to 0, C\to 0, \omega\to 0\ \ as\ y\to\infty \end{array}\right\}$$

(12)

where Gr is the thermal Grashof number, M is the Hartmann number, Gc is the mass Grashof number, Sc is the Schmidt number, Pr is the Prandtl number, K is the permeability Parameter and k is the chemical reaction parameter.

Also,

$$\eta=\frac{\eta^* v}{v_0^2}, K=\frac{K^* v_0^2}{v^2}, \gamma=\mu j^*(1+\frac{1}{2}\beta), j^*=\frac{v_0^2 j^*}{v^2},$$

$$\beta=\frac{\nu}{\mu}, \Pr=\frac{\nu^2}{\alpha}, M=\frac{\sigma B_0 \nu}{\rho v_0^2},$$

$$Gr=\frac{g\beta\nu(T_\omega-T_\infty)}{u_0 v_0}, Gc=\frac{g\beta c\nu(C_\omega-C_\infty)}{u_0 v_0}$$

III. METHOD OF SOLUTION

To solve (8), (9), (10) and (11) subject to the boundary conditions (12), we assume solutions of the form

$$u(y,t)=\sum_{k=0}^{1} u_k \varepsilon^k e^{k\,\mathrm{int}} \qquad (13)$$

$$F(y,t)=\sum_{k=0}^{1} f_k \varepsilon^k e^{k\,\mathrm{int}} \qquad (14)$$

$$G(y,t)=\sum_{k=0}^{1} g_k \varepsilon^k e^{k\,\mathrm{int}} \quad (15)$$

$$H(y,t)=\sum_{k=0}^{1} h_k \varepsilon^k e^{k\,\mathrm{int}} \quad (16)$$

Substituting (13), (14), (15) and (16) into (8), (9), (10) and (11) respectively, Comparing harmonic and non-harmonic terms, we obtain

$$\frac{d^2u_0}{dy^2}+\frac{1}{(1+\beta)}\frac{du_0}{dy}-P_1u_0= \frac{1}{(1+\beta)}\left[B-Grg_0-Gch_0-2\beta\frac{df_0}{dy}\right] \quad (17)$$

$$\frac{d^2 f_0}{dy^2}+\eta\frac{df_0}{dy}=0 \quad (18)$$

$$\frac{d^2g_0}{dy^2}+\Pr\frac{dg_0}{dy}=0 \quad (19)$$

$$\frac{d^2h_0}{dy^2}+Sc\frac{dh_0}{dy}=0 \quad (20)$$

and the boundary conditions become

$$\left.\begin{array}{l} y=0: u_0-u_p=0,\ f_0=-u_p'',\ g_0=1, h_0=1 \\ y\to\infty: u_0=1,\ f_0\to 0, g_0\to 0, h_0\to 0 \end{array}\right\} \quad (21)$$

Also,

$$\frac{d^2u_1}{dy^2}+\frac{1}{(1+\beta)}\frac{du_1}{dy}-P_2u_1= -\frac{1}{(1+\beta)}\left[Grg_1+Gch_1+2\beta\frac{df_1}{dy^2}+\frac{A}{(1+m^2)}\frac{du_1}{dy}\right] \quad (22)$$

$$\frac{d^2 f_1}{dy^2}+\eta\frac{df_1}{dy}-in\Pr f_1=-A\Pr\frac{df_0}{dy} \quad (23)$$

$$\frac{d^2g_1}{dy^2}+\Pr\frac{dg_1}{dy}-in\Pr g_1=-A\Pr\frac{dg_0}{dy} \quad (24)$$

$$\frac{d^2h_1}{dy^2}+Sc\frac{dh_1}{dy^2}-inSch_1=-ASc\frac{dh_0}{dy} \quad (25)$$

Subject to the boundary conditions

$$\left.\begin{array}{l} y=0: u_1=0,\ f_0=, g_1=1, h_1=1 \\ y\to\infty: u_1=1,\ f_1\to 0, g_1\to 0, h_1\to 0 \end{array}\right\} \quad (26)$$

Solving (17) to (25) under the boundary conditions (21) and (26) and substituting the obtained solutions into (13) to (16). Then the velocity distribution is given by

$$u(y,t)=\left(L_1e^{\left(-\frac{1}{2(1+\beta)}+a\right)y}+L_2e^{-\left(\frac{1}{2(1+\beta)}+a\right)y}+L_3+L_4e^{-\Pr y}+L_5e^{-Scy}+L_6e^{-\eta y}\right)$$
$$+\varepsilon e^{\mathrm{int}}\left(\begin{array}{l} L_7e^{-\left(\frac{1}{2(1+\beta)}+f\right)y}+L_8e^{-\left(\frac{1}{2(1+\beta)}\right)y}+L_9e^{-m_4y}+L_{10}e^{-\Pr y}+L_{11}e^{-m_3y}+L_{12}e^{-Scy}+L_{13}e^{-m_5y}+L_{14}e^{-\eta y}+L_{15}e^{m_1y} \\ +L_{16}e^{-m_2y}+L_{17}e^{-\Pr y}+L_{18}e^{-Scy}+L_{19}e^{-\eta y} \end{array}\right) \quad (27)$$

The angular velocity distribution is

$$F(y,t)=L_{20}e^{-\eta y}+\varepsilon e^{\mathrm{int}}(L_{21}e^{-m_5y}+L_{22}e^{-\eta y}) \quad (28)$$

The temperature distribution is expressed as

$$G(y,t)=e^{-\Pr y}+\varepsilon e^{\mathrm{int}}(L_{23}e^{-m_4y}+L_{24}e^{-\Pr y}) \quad (29)$$

The concentration distribution is given by

$$H(y,t)=e^{-Scy}+\varepsilon e^{\mathrm{int}}(L_{25}e^{-m_3y}+L_{26}e^{-Scy}) \quad (30)$$

The skin friction from (27) is

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$$C_f = \left.\frac{\partial u(y,t)}{\partial y}\right|_{y=0} = \left(-(\frac{1}{2(1+\beta)} + a)L_{27} - \Pr L_4 - ScL_5 - \eta L_6 \right)$$

$$+\varepsilon e^{\text{int}} \left(\begin{array}{l} (\frac{1}{2(1+\beta)} + f)L_{28} - m_4 L_9 - \Pr L_{10} - m_3 L_{11} - ScL_{12} - m_5 L_{13} - \eta L_{14} - m_1 L_{15} - m_2 L_{16} \\ -\Pr L_{17} - ScL_{18} - \eta L_{19} \end{array} \right)$$

IV. RESULTS AND DISCUSSION

Micropolar fluid behavior on convective boundary layer flow with constant pressure, permeability, heat and mass transfer has been solved analytically in the previous section. Computations are performed in order to understand the flow nature of the fluid for different parameters embedded in the problem such as Gr, M, m, Gc, n, t, Sc, B, Pr, β and Up.

Figure 1 represents the concentration profile, Figure 2 is the temperature profile, Figures 3 – 6 are the angular velocity profiles and Figures 7 – 14 represent the velocity profiles with varying parameters respectively.

The effect of concentration for different values of (Sc = 0.18, 0.3, 0.6, 0.8) is presented in Figure 1. The graph shows that concentration decreases with increase in Sc.

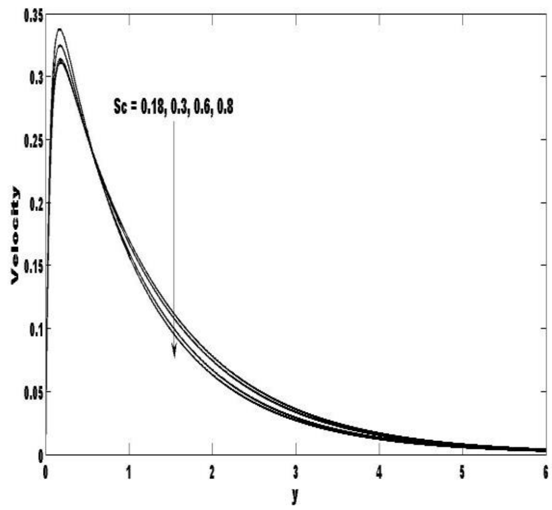

Figure 1. Concentration Profiles for Different Values of Sc.

In Figure 2, the effect of temperature for different values of (Pr = 0.71, 1, 3, 7) is shown. The graph illustrates that temperature decreases with increase in Pr.

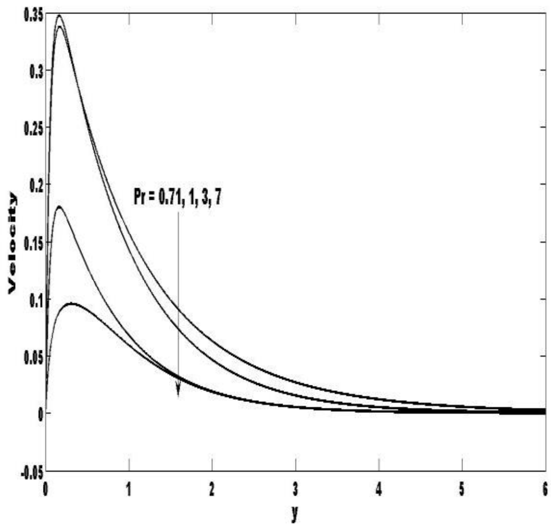

Figure 2. Temperature profiles for different values of Pr.

The effect of angular velocity for different values of (β = 0.2, 0.6, 0.8, 2) is given in Figure 3. Also, the effect of angular velocity for different values of (Up = 0, 0. 3, 0.6, 1) is shown in Figure 4. Figure 5 denotes the effect of angular velocity for (n = 0.1, 0.3, 0.7, 1). The effect of angular velocity for different values of (t = 0.5, 1, 1.5, 2) is given in figure 6. The graph show that angular velocity decreases with the increase in β , Up, n and t respectively.

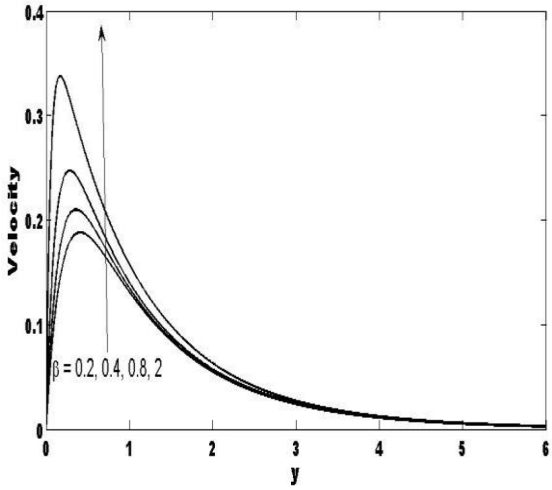

Figure 3. Angular velocity profiles plotted for different values of β .

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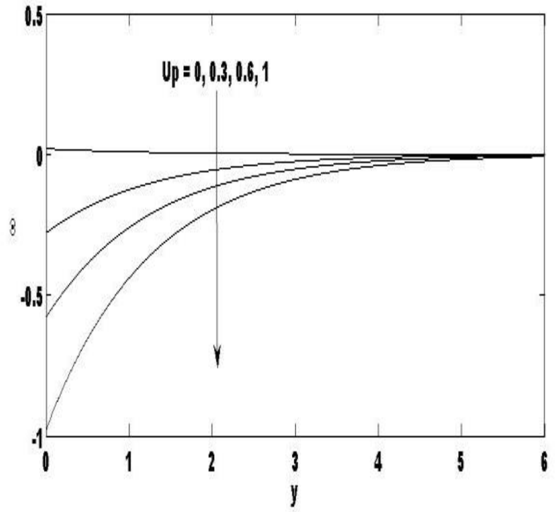

Figure 4. Angular velocity profiles for different values of Up.

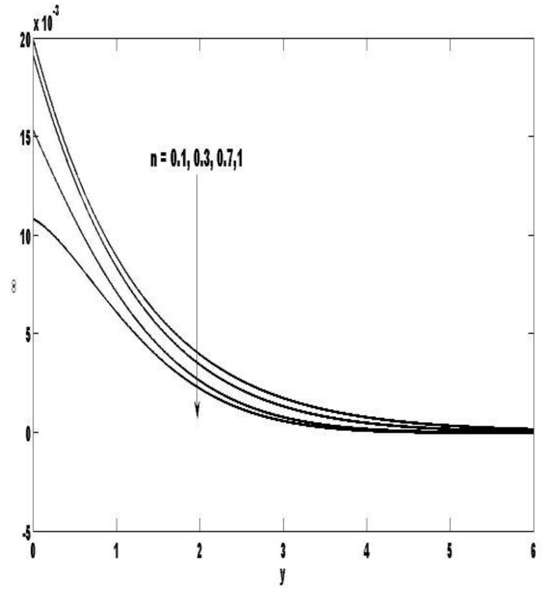

Figure 5. Angular velocity profiles for different values of n.

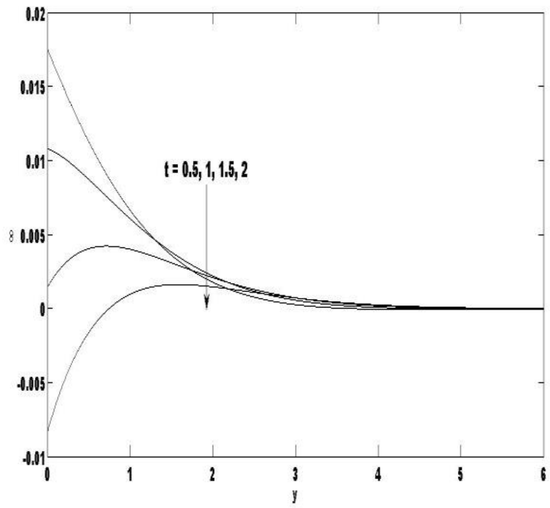

Figure 6. Angular velocity profiles for different values of t.

The effect of Schmidt number for (Sc = 0.18, 0.3, 0.6, 0.8) on velocity is presented in Figure 7.

Similarly, the effect of velocity for different values of (Pr = 0.71, 1, 3, 7) is given in Figure 8 and Figure 9 denotes the effect of velocity for (Gr = 2, 3, 4, 7). The effect of velocity for different values of (Gc = 2, 3, 4, 7) is presented in Figure 10. The graphs show that velocity increases with the increase in Gc, Gr and decreases with the increase in Sc and Pr.

T he effect of velocity for different values (M = 1, 2, 3, 5) is presented in Figure 11. The effect of velocity for different values of (Up = 0, 0.3, 0.6, 1) is shown in Figure 12, the effect of velocity for different values of (β = 0.1, 0.3, 0.6, 1) is given in Figure 13. Figure 14 depicts the effect of velocity for (m = 1, 2, 3, 5). The graphs show that velocity decreases with increase in M, m and β and decreases with the increase in Up. The effect of velocity for different values (B = 0, 0.5, 1, 1.5) is presented in Figure 15 and the effect of velocity for different values of (n = 0.1, 0.6, 1, 3) is shown in Figure 16. The graphs show that velocity decreases with increase in n and B.

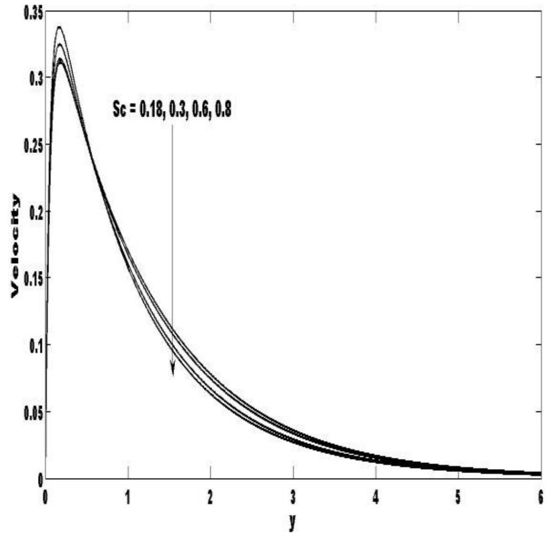

Figure 7. Velocity profiles for different values of Sc.

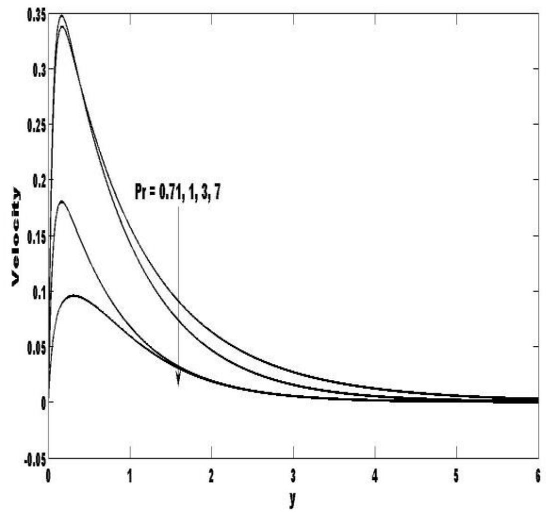

Figure 8. Velocity profiles for different values of Pr.

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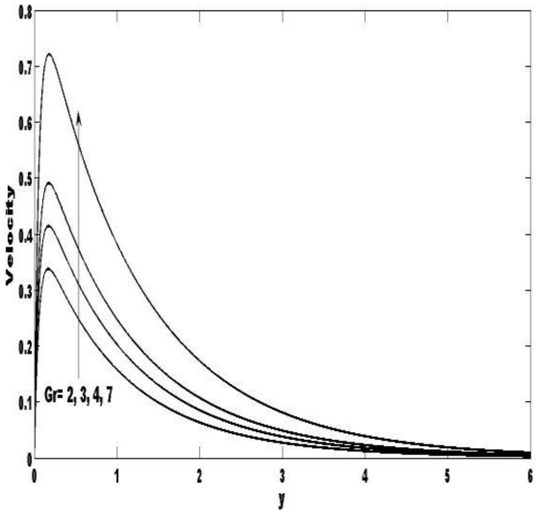

Figure 9. Velocity profiles for different values of Gr.

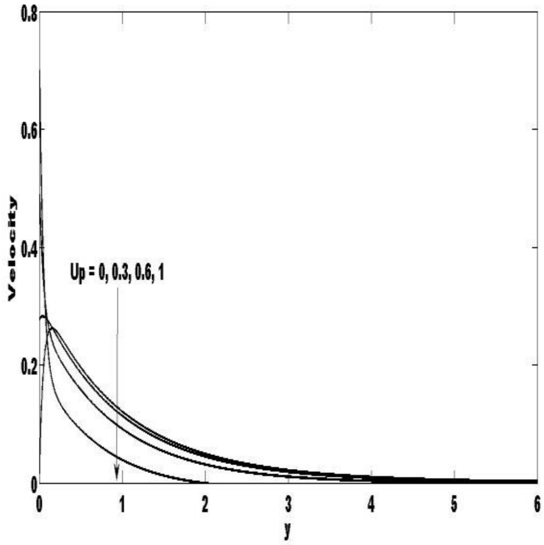

Figure 12. Velocity profiles for different values of Up.

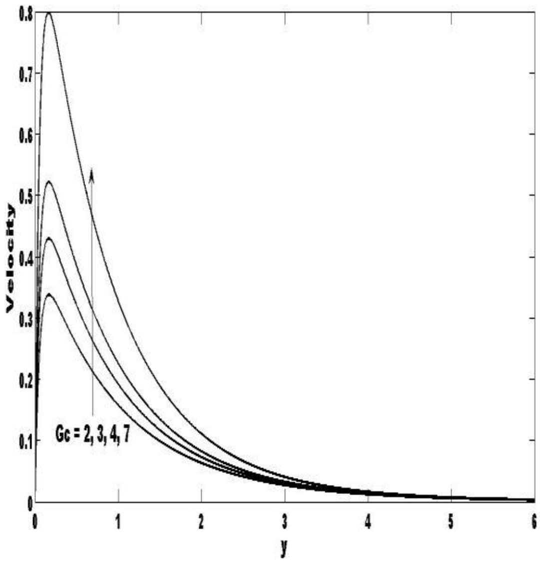

Figure 10. Velocity profiles for different values of Gc.

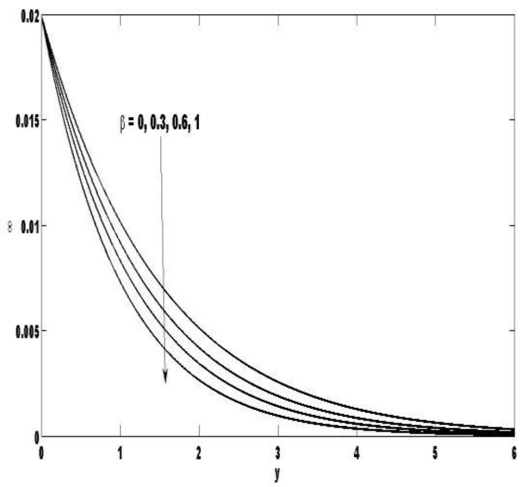

Figure 13. Velocity profiles for different values of β.

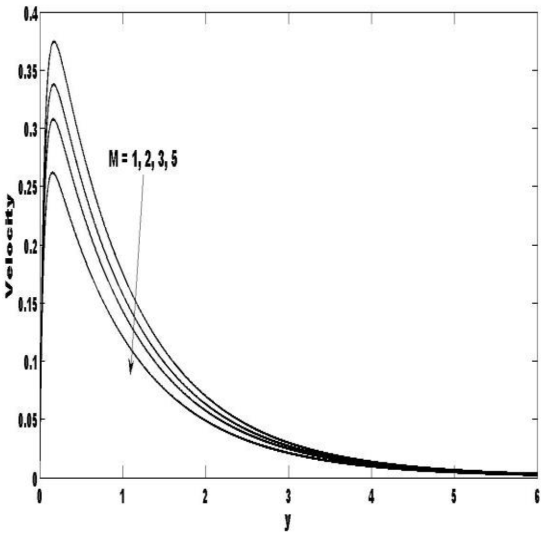

Figure 11. Velocity profiles for different values of M.

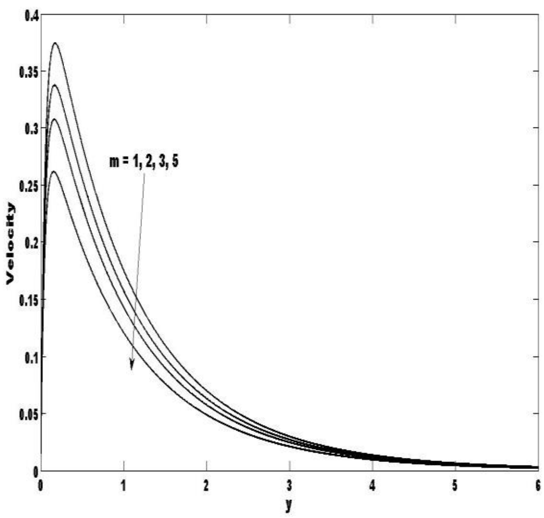

Figure 14. Velocity profiles for different values of

m.

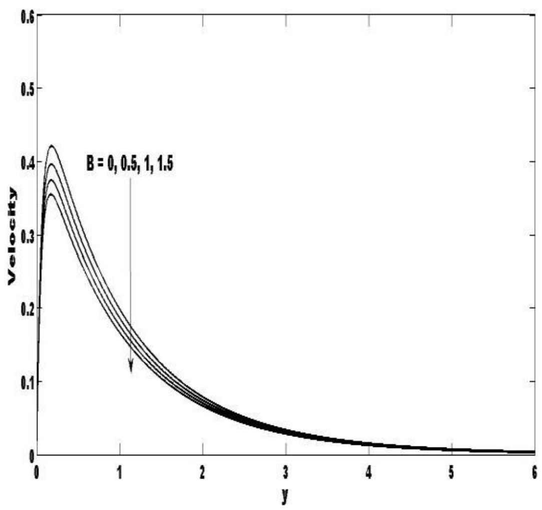

Figure 15. Velocity profiles for different values of B.

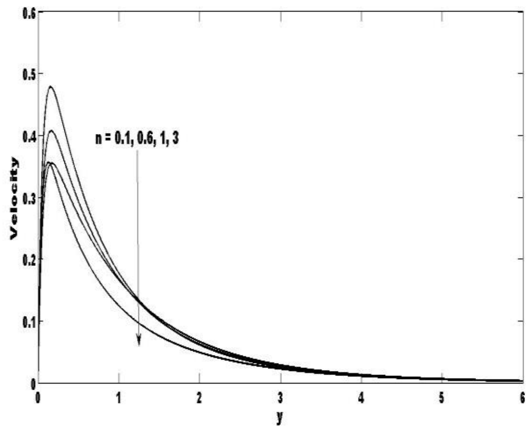

Figure 16. Velocity profiles for different values of n.

Table 1 represents the Skin friction, it shows that Skin friction increases with rise in Gc and Gr and decreases with the increase in Sc, ω, Pr, m, K, ε and M.

Table 1: Skin friction τ

ε	n	Pr	Sc	K	Gc	Gr	M	m	β	τ
0.2	1	0.71	0.3	0.1	2	3	4	1	0.3	0.5213
0.4	1	0.71	0.3	0.1	2	3	4	1	0.3	0.5011
0.2	**3**	0.71	0.3	0.1	2	3	4	1	0.3	0.4924
0.2	1	**1**	0.3	0.1	2	3	4	1	0.3	0.5156
0.2	1	0.71	**0.6**	0.1	2	3	4	1	0.3	0.4973
0.2	1	0.71	0.3	**0.3**	2	3	4	1	0.3	0.5172
0.2	1	0.71	0.3	0.1	**4**	3	4	1	0.3	0.5036
0.2	1	0.71	0.3	0.1	2	**5**	4	1	0.3	0.7217
0.2	1	0.71	0.3	0.1	2	3	**8**	1	0.3	0.6251
0.2	1	0.71	0.3	0.1	2	3	4	1	**0.5**	0.5125
0.2	1	0.71	0.3	0.1	2	3	4	**3**	0.3	0.4981
0.2	1	0.71	0.3	0.1	2	3	4	1	0.3	0.5201

V. CONCLUSION

Micropolar fluid behavior on steady/unsteady convective boundary layer flow with constant pressure, permeability, heat and mass transfer under the influence of a transverse magnetic field was studied. The approximate solutions of the governing equations were obtained by perturbation technique and the physical situation is depicted graphically. Important findings from this study are as follows:

1. The velocity becomes higher when thermal Grashof and mass Grashof numbers are increased while a reverse trend is observed for increased Magnetic parameter, Schmidt and Prandtl numbers.
2. The angular velocity decreases with increased time.
3. The temperature reduces with increased Prandtl and a similar trend is observed in the concentration when Schmidt number becomes higher
4. The skin friction increases with rise in permeability, thermal Grashof and mass Grashof numbers while it retards as Schmidt and Prandtl numbers become significant.

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