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Hall Current and Thermal Radiation Effects on Heat and Mass Transfer of Unsteady MHD Flow of a Viscoelastic Micropolar Fluid through a Porous Medium

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ABSTRACT

The present paper is concerned to analyze the effect of hall current on heat and thermal radiation and mass transfer of unsteady MHD flow of a viscoelastic micropolar fluid through a porous medium with chemical reaction. The governing partial differential equations are transformed to dimensionless equations using dimensionless variables. The dimensionless governing equations are then solved analytically using perturbation technique. The effects of various governing parameters on the velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number are shown in figures and tables and analyzed in detail.

1. Introduction

The Magneto-Hydrodynamics (MHD) boundary layers with heat and mass transfer over flat surfaces are found in many engineering and geophysical applications such as geothermal reservoirs, thermal insulation, enhanced oil recovery, packed-bed catalytic reactors, cooling of nuclear reactors. Because of this reason, many researchers tend to apply the MHD flow into their problems. For instance, Khaleque and Samad [1] examined the effects of radiation heat generation and viscous dissipation on MHD free convection flow along a stretching sheet. Amkadni and Azzouzi [2] studied the similarity solution of MHD boundary layer flow over a moving vertical cylinder. Meanwhile, Rajeswari *et al*., [3] analyzed the influence of chemical reaction parameter, magnetic parameter, buoyancy parameter and suction parameter on nonlinear MHD boundary layer flow through a vertical porous surface.

Radiative heat and mass transfer play an important role in manufacturing industries for the design of fins, steel rolling, nuclear power plants, and gas turbines. Various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering applications. If the

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temperature of the surrounding fluid is rather high, radiation effects play an important role and this situation exists in space technology. In such cases, one has to take into account the effect of thermal radiation and mass diffusion. England and Emery [4] studied thermal radiation effects of an optically thin grey gas bounded by a stationary vertical plate. Radiation effects on mixed convection along an isothermal vertical plate were also studied by Hossain and Takhar [5]. Raptis and Perdikis [6] studied the effects of thermal radiation and free convection flow past a moving vertical plate, the governing equations were solved analytically. Das *et al.,* [7] analyzed radiation effects on flow past an impulsively started infinite isothermal vertical plate.

The effects of chemical reaction and radiation absorption on free convective flow through a porous medium with a variable suction in the presence of uniform magnetic field were studied by Sudheer Babu and Satyanarayana [8]. Ahmed and Alam Sarker [9] presented the problem of a steady two - dimensional natural convective flow of a viscous incompressible and electrically conducting fluid past a vertical impermeable flat plate in the presence of a uniform transverse magnetic field. Saravana *et al*., [10] studied the effects of mass transfer on the MHD viscous flow past an impulsively started infinite vertical plate with constant mass flux. Lavanya [11] studied MHD rotating flow through a porous medium with heat and mass transfer. Few other related studies can be found in [12-16].

In the present paper, we extend our previous work by incorporating concentration equations with thermal radiation term to study hall current and thermal radiation effect on heat and mass transfer of unsteady MHD flow of a viscoelastic micropolar fluid through a porous medium. The governing Equations are solved analytically using perturbation method and effect of various physical parameters are discussed numerically and graphically.

2. Methodology

We consider the unsteady flow of a viscous incompressible and electrically conducting viscoelastic micropolar fluid over an infinite vertical porous plate, subjected to a constant transverse magnetic field B_0 in the presence of thermal and concentration buoyancy effects. The induced magnetic field is assumed to be negligible compared to the applied magnetic field. The *x*-axis is taken along the planar surface in the upward direction and the y-axis taken to be normal to it as shown in figure 1. Due to the infinite plane surface assumption, the flow variables are function of y and t only. The plate is subjected to a constant suction velocity v_0.

The governing equations of flow under the usual Boussinesq approximation are given by

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

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial y}=(\nu+\nu_r)\frac{\partial^2 u}{\partial y^2}-K_0\frac{\partial^3 w}{\partial t\partial y^2}+\nu_r\frac{\partial N_1}{\partial y}+g\beta_T(T-T_\infty)+g\beta_C(C-C_\infty)-\sigma\frac{B_0^2(u+mw)}{\rho(1+m^2)}-\frac{\nu}{k}u \tag{2}$$

$$\frac{\partial w}{\partial t}+v\frac{\partial w}{\partial y}=(\nu+\nu_r)\frac{\partial^2 w}{\partial y^2}-K_0\frac{\partial^3 w}{\partial t\partial y^2}+\nu_r\frac{\partial N_2}{\partial y}-\sigma\frac{B_0^2(w-mu)}{\rho(1+m^2)}-\frac{\nu}{k}w \tag{3}$$

$$\rho J\left(\frac{\partial N_1}{\partial t}+v\frac{\partial N_1}{\partial y}\right)=\gamma\frac{\partial^2 N_1}{\partial y^2} \tag{4}$$

$$\rho J\left(\frac{\partial N_2}{\partial t}+v\frac{\partial N_2}{\partial y}\right)=\gamma\frac{\partial^2 N2}{\partial y^2} \tag{5}$$

$$\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} \tag{6}$$

$$\frac{\partial C}{\partial t}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-k_r(C-C_\infty) \tag{7}$$

The appropriate boundary conditions for the problem are

$$u=L\left(\frac{\partial u}{\partial y}\right),\quad w=L\left(\frac{\partial u}{\partial y}\right),\quad N_1=-n\left(\frac{\partial u}{\partial y}\right),\quad N_2=-n\left(\frac{\partial w}{\partial y}\right),$$
$$T=T_\infty+(T_w-T_\infty)e^{iwt}$$
$$C=C_\infty+(C_w-C_\infty)e^{iwt}\quad at\quad y=0 \tag{8}$$
$$u\to 0,\ w\to 0\ N_1\to 0,$$
$$N_2\to 0,\ T\to T_\infty,\ C\to C_\infty \text{ at } y\to\infty$$

where *u*, *v* and *w* are velocity components along x, y and z -axis respectively. v is the kinematic viscosity, g is the acceleration due to gravity, β_T and β_c are the coefficients of thermal expansion and concentration expansion respectively, T is the dimensional temperature of the fluid, T_w and T_∞ denotes the temperature at the plate and temperature far away from the plate respectively, C is the dimensional concentration of the solute, C_w and C_∞ are concentration of the solute at the plate and concentration of the solute far from the plate respectively, K is the permeability of the porous medium, k is the thermal conductivity of the medium, ρ is the density of the fluid, j is the micro inertia density or micro inertia per unit mass, γ is the spin gradient viscosity, L is the characteristic length, w is the dimensional frequency of oscillation, σ is the electrical conductivity, m is the hall current parameter and D is the molecular diffusivity, q_r is the radiative heat flux.

The constant that related to microgyration vector and shear stress is n, where $0\le n\le 1$. The case n=0 represents concentrated particle flows in which the microelement close to the wall surface are unable to rotate. thios case is also known as the strong concentration of microelements. the case n=1 is used for the vanishing of anti-symmetric part of the stress tensor and denotes weak concentration of microelements. the case n=1 is used for the modeling of turbulent boundary layer flows, we shall consider n=0 and n=0.5.

Following Rosseland approximation the radiative heat flux q_r is modeled as

$$q_r=\frac{4\sigma}{3k}\frac{\partial T^4}{\partial y} \tag{9}$$

where σ is the stefan-Boltzman constant and k is the mean absorption coefficient. Assuming that the difference in temperature within the flow are such that T^4 can be expressed as a linear combination of the temperature, we expand T^4 in taylor's series about T_∞ as follows:

$$T^4=T_\infty^4+4T_\infty^3(T-T_\infty)+6T_\infty^2(T-T_\infty)^2+-- \tag{10}$$

and neglecting higher order terms beyond the first degree in $(T-T_\infty)$, we have

$$T^4\approx -3T_\infty^4+4T_\infty^3 T \tag{11}$$

Differentiating equation (9) with respect to y and using equation (11) to obtain

$$\frac{\partial q_r}{\partial y}=\frac{-16T_\infty^3\sigma}{3k}\frac{\partial_2 T}{\partial y^2} \tag{12}$$

Let us introduce the following dimensionless variables:

$$u=\frac{u'}{v_0},\quad v=\frac{u'}{v_0},\quad w=\frac{w'}{v_0},\quad \eta=\frac{v_0 y'}{v},\quad N_1=\frac{vN_1'}{v_0^2},\quad N_2=\frac{vN_2'}{v_0^2},\quad t=\frac{t'V_0^2N_1}{4v},\quad w=\frac{4vw'}{v_0^2},\ h=\frac{V_0L}{v}$$

$$,\ \theta=\frac{T'-T'_\infty}{T'_w-T_\infty'},\quad C=\frac{C'-C'_\infty}{C'_w-C_\infty'}\ J=\frac{v_0{}^2J'}{v^2} \tag{13}$$

Substituting Equation (13) into equations (2)-(8) yield the following dimensionless equations:

$$\frac{1}{4}\frac{\partial u}{\partial t}-\frac{\partial u}{\partial \eta}=(1+\beta)\frac{\partial^2 u}{\partial \eta^2}-a\frac{\partial^3 u}{\partial t\partial \eta^2}+\beta\frac{\partial N_1}{\partial \eta}-\frac{M}{1+m^2}(mw+u)+Gr\theta+GcC-\frac{u}{k} \tag{14}$$

$$\frac{1}{4}\frac{\partial w}{\partial t}-\frac{\partial w}{\partial \eta}=(1+\beta)\frac{\partial^2 u}{\partial \eta^2}w-a\frac{\partial^3 w}{\partial t\partial \eta^2}-\beta\frac{\partial N_2}{\partial \eta}-\frac{M}{1+m^2}(w-mw)-\frac{u}{k} \tag{15}$$

$$\frac{1}{4}\frac{\partial N_1}{\partial t}-\frac{\partial N_1}{\partial \eta}=L\frac{\partial^2 N_1}{\partial \eta^2} \tag{16}$$

$$\frac{1}{4}\frac{\partial N_2}{\partial t}-\frac{\partial N_2}{\partial \eta}=L\frac{\partial^2 N_2}{\partial \eta^2} \tag{17}$$

$$\frac{1}{4}\frac{\partial \theta}{\partial t}-\frac{\partial \theta}{\partial \eta}=\frac{1}{pr}(1+N_r)\frac{\partial^2 \theta}{\partial \eta^2} \tag{18}$$

$$\frac{1}{4}\frac{\partial C}{\partial t}-\frac{\partial C}{\partial \eta}=\frac{1}{Sc}\frac{\partial^2 C}{\partial \eta^2}-K_rC \tag{19}$$

Where $\beta=v_r/v$ is the dimensionless viscosity ratio, $a=K_0v_0^2/4v^2$ is the viscoelastic parameter, $M=\sigma B_0^2 v/\rho V_0^2$ is the magnetic field parameter , $N_r=16T_\infty{}'\sigma'/3k'k$ is the thermal radiation parameter, $Gr=v\beta_t g(T_w'-T_\infty')/V_0^3$ is the Grashof number, $Gc=v\beta_t g(C_w'-C_\infty')/V_0^3$ is the modified Grashof number , $pr=v\rho Cp/k$ is the prandtl number is the schmidt number, $Sc=v/D$ is the permeability of the porous medium parameter and $L=\gamma V_0^2/\rho v^3 j$ is the material parameter
Also the boundary conditions becomes

$$u=h\frac{\partial u}{\partial \eta},\quad w=h\frac{\partial w}{\partial \eta},\quad \theta=e^{iwt},\quad C=e^{iwt},\quad N_1=-n\frac{\partial u}{\partial \eta},\quad N_2=-n\frac{\partial w}{\partial \eta}\qquad \text{at}\qquad y=0$$

$$u\to 0,\ w\to 0,\theta\to 0,\ C\to 0,\ N_1\to 0,\ N_2\to 0,\ \text{at}\ y\to\infty \tag{20}$$

$$\frac{1}{4}\frac{\partial q}{\partial t}-\frac{\partial q}{\partial \eta}=(1+\beta)\frac{\partial^2 q}{\partial \eta^2}-a\frac{\partial^3 q}{\partial t\partial \eta^2}+$$

$$i\beta\frac{\partial p}{\partial \eta}-\frac{M}{1+m^2}(1-im)q+Gr\theta+GcC-\frac{q}{k} \tag{21}$$

$$\frac{1}{4}\frac{\partial p}{\partial t}-\frac{\partial p}{\partial \eta}=L\frac{\partial^2 p}{\partial \eta^2} \tag{22}$$

$$\frac{1}{4}\frac{\partial\theta}{\partial t}-\frac{\partial\theta}{\partial\eta}=\frac{1}{pr}(1+N_r)\frac{\partial^2\theta}{\partial\eta^2} \quad (23)$$

$$\frac{1}{4}\frac{\partial C}{\partial t}-\frac{\partial C}{\partial\eta}=\frac{1}{Sc}\frac{\partial^2 C}{\partial\eta^2}-K_r C \quad (24)$$

and the corresponding boundary conditions are

$$q=h\frac{\partial q}{\partial\eta},\quad \theta=e^{iwt},\quad C=e^{iwt},\quad P=in\frac{\partial q}{\partial\eta}\quad \text{at}\quad y=0$$

$$q\to 0,\quad \theta\to 0,\quad C\to 0,\quad p\to 0,\quad \text{at}\quad y\to\infty \quad (25)$$

2.1 Method of Solution

In order to solve equations (21)-(24) subject to the boundary conditions (25), we assume a perturbation method of this form:

$$q=q_0(\eta)e^{iwt},\quad p=p_0(\eta)e^{iwt},\quad \theta=\theta_0(\eta)e^{iwt},\quad C=C_0(\eta)e^{iwt} \quad (26)$$

2.2 Calculation

Substituting equation (26) in to equations (21)-(24), we obtain the following set of equations:

$$(a_1-ia_2)q_0''+q_0'-(a_3+ia_4)q_0=$$
$$Gr\theta_0-GcC_0-i\beta p_0' \quad (27)$$

$$LP_0''+P_0'-\frac{iw}{4}p_0=0 \quad (28)$$

$$a_5\theta_0''+\theta_0'-\frac{iw}{4}\theta_0=0 \quad (29)$$

$$C_0''+ScC_0'-\frac{KrSciw}{4}C_0=0 \quad (30)$$

where $a_1=1+\beta,\ a_2=a\omega,\ a_3=M/1+m^2+1/k,\ a_4=(\omega/4)-(Mm^2/1+m^2),\quad a_5=(1+Nr)/\Pr$
The corresponding boundary conditions can be written as

$$q_0=h\frac{\partial q_0}{\partial n},\quad \theta_0=1,\quad C_0=1,\quad p_0=in\frac{\partial q_0}{\partial n},\quad \text{at y = 0}$$

$$q_0=0,\quad \theta_0=0,\quad C_0=0,\quad p_0=1,\quad \text{at}\quad y\to\infty, \quad (31)$$

The solution of Eqs. (27)-(30) satisfying the boundary conditions 31 are given by thickness which is expected since when the holes porous medium

$$q=(A_4e^{-m4y}+A_1e^{-m2y}+A_2e^{-m1y}+A_3e^{-m3y})e^{i\omega t}\quad p=B_1e^{iwt-m3y}$$
$$\theta=e^{iwt-m2y}$$
$$C=e^{iwt-m1y}$$

The skin-friction, Nusselt number and Sherwood number are important physical parameters for this type of boundary layer flow. these parameters can be defined and determined as follows.

$$C_f = \left(\frac{\partial q}{\partial y}\right)_{y=0} = (m_4 A_4 + m_2 A_1 + m_1 A_2 + m_3 A_3)e^{i\omega t}$$

The rate of heat transfer at the surface in terms of nusselt number is given by

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = m_2 e^{i\omega t}$$

The rate of mass transfer at the surface in terms of the local sherwood number is given by

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = m_3 e^{i\omega t}$$

3. Results and Discussions

The results are presented as velocity, temperature and concentration profiles in the below graphs. The effects of magnetic field parameter on velocity distribution profiles across the boundary layer are presented in Fig-1. It is obvious that the effect of increasing values of the magnetic field parameter M results in a decreasing velocity distribution across the boundary layer. This is due to fact that the effect of a transverse magnetic field give rise to a resistive type force called the lorentz force. The force has the tendency to slow the motion of the fluid.

Figure 2 depicts the effects of permeability of the porous medium parameter(k) on velocity distribution profiles and it is obvious that as permeability parameter (k) increases, the velocity increases along the boundary layer become larger, the resistivity of the medium may be neglected.

Figure 3 shows the translation velocity profiles with different values of radiation parameter and the effect of increasing the radiation parameter is to increase the translational velocity. This is because when the intensity of heat generated through radiation increased, the bond holding the components of the fluid particles is easily broken and the fluid velocity will increase.

Figure 4 displays the effect of Hall current parameter on the translational velocity distribution profiles. It is noticed that the hall current parameter increases the velocity. Figures 5 and 6 illustrates the effect of parameter on micro rotational velocity profiles. The profiles increase as the parameter increases and presents the effect of the Prandtl number (*Pr*) on the temperature profiles. Increasing the value of pr has the tendency to decrease the fluid temperature in the boundary layer as well as the thermal boundary layer thickness. This causes the wall slope of the temperature to decrease as pr is increasing as causing the Nusselt number to increase as can be clearly seen.

The numerical result of skin friction, Nusselt number and Sherwood number are shown in the tables 1-2. Table 1 shows the effect of *Pr* and radiation parameter (N) on the Nusselt number increases as *Pr* increases. This shows that the surface heat transfer from the porous plate increases with the increasing values of *Pr* and decreases with increasing value of N. Table 2 shows that the effect of increasing the Sc is to increases the nusselt number also increases.

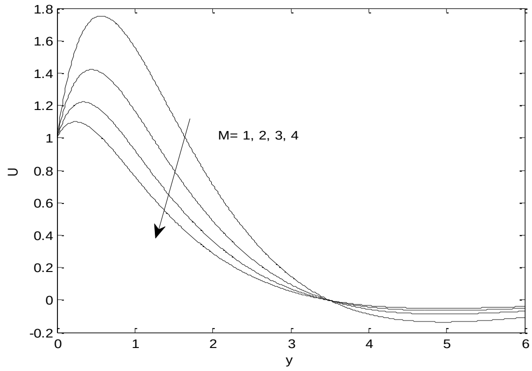

Fig. 1. Effects of magnetic parameter on velocity Profiles

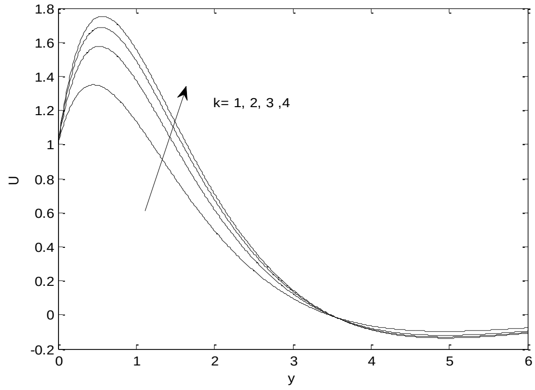

Fig. 2. Effects of permeability parameter on velocity profiles

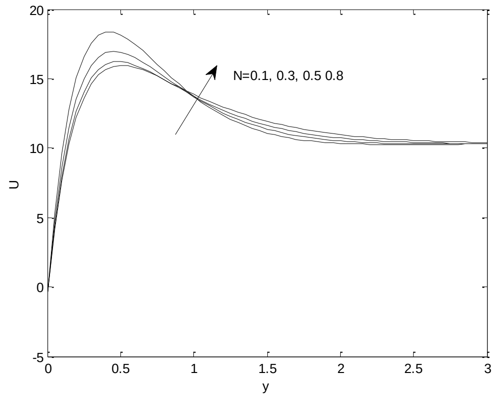

Fig. 3. Velocity profiles for different values of N

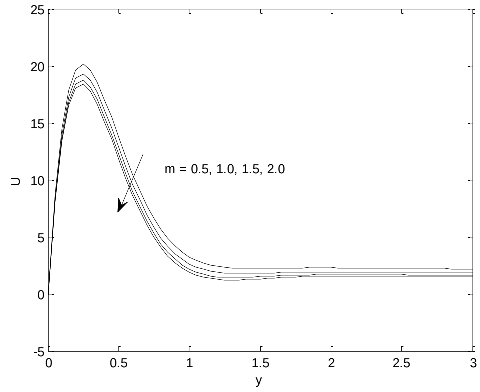

Fig. 4. Velocity profiles for different values of m

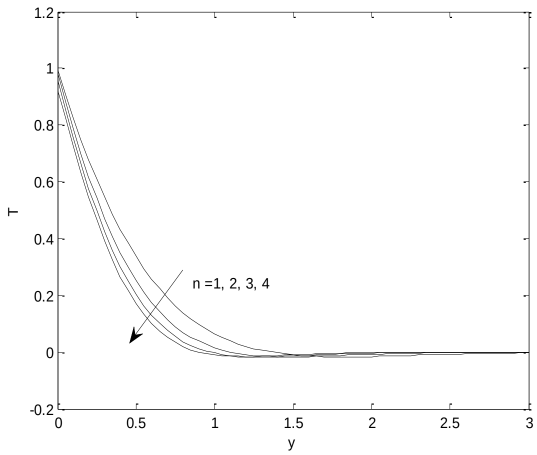

Fig. 5. Temperature profiles for different values of n

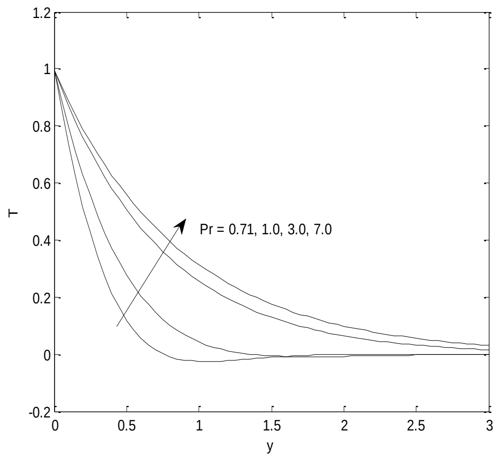

Fig. 6. Temperature profiles for different values of *Pr*

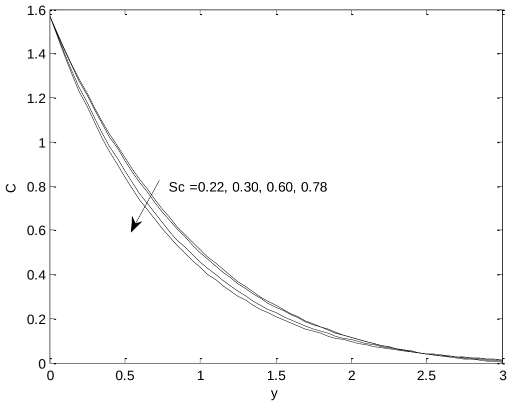

Fig. 7. Concentration profiles for different values Schmidt number

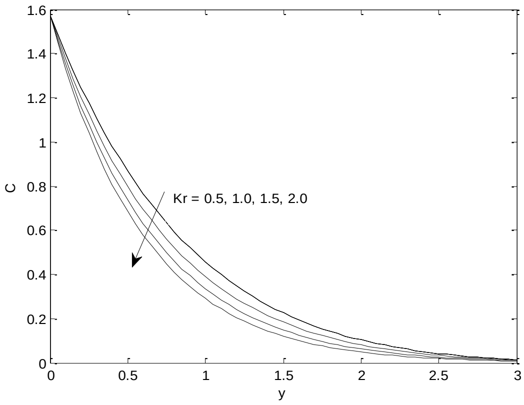

Fig. 8. Concentration profiles for different values of chemical reaction parameter

Table 1
Effects of Pr and N on Nusselt number Nu

Pr	*N*	*Nu*
3	0.5	1.9661
4	0.5	2.6176
5	0.5	3.2716
3	0.2	2.4544
3	0.4	2.1054
3	0.8	1.6421

Table 2
Effects of *Sc* on Sherwood number, *Sh*

Sc	*Nu*
2	1.9661
3	2.9444
4	3.9271

4. Conclusions

The study of MHD heat and mass transfer flow of an incompressible, electrically conducting viscoelastic micropolar fluid over an infinite vertical plate through porous medium was conducted. The results are discussed through graphs and tables for different values of parameters. Following conclusions can be drawn from the results obtained:

- The Nusselt number increased as the prandtl number increased and decreased as radiation parameter increased.
- The Sherwood number increased as the Schmidt number increased.
- In the presence of a uniform magnetic field, increase in the strength of the applied magnetic field decelerated the fluid motion along the wall of the plate inside the boundary layer.

- Increase in hall current parameter increases the momentum and thermal boundary layer thickness.
- The radiation parameter increases both skin friction coefficient and couple stress coefficient.

Appendix:

$$m_1 = \frac{-Sc + \sqrt{Sc^2 + i\omega Sc}}{2}, \quad m_2 = \frac{-1 + \sqrt{1 + a_5 i\omega}}{2}, \quad m_3 = \frac{-1 + \sqrt{1 + 4\frac{Li\omega}{4}}}{2},$$

$$T_1 = a_1 - ia_2, \quad T_2 = a_3 - ia_4, \quad m_4 = \frac{-1 + \sqrt{1 + 4T_1T_2}}{2T_1}, \quad A_1 = \frac{-Gr}{T_1 m_2^2 - m_2 - (a_3 + ia_4)}$$

$$A_2 = \frac{-Gc}{T_1 m_1^2 - m_1 - (a_3 + ia_4)}, \quad A_3 = \frac{-\beta n m_3 T}{T_1 m_3^2 - m_3 - (a_3 + ia_4)}, \quad A_4 = hT - A_1 - A_2 - A_3$$

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