Hall Current And Radiation Effects On a Natural Convection MHD Flow Through Porous Media In A Rotating System With Inclined Magnetic Field

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Abstract

In the present pape, Hall current and radiation effects on a natural convection MHD flow in a rotating system with inclined magnetic field are studied. The fluid considered is viscous, incompressible and electrically conducting. The flow is modeled with the help of partial differential equations. The set of governing equations are solved by Laplace transform method. The results obtained have been analyzed with the help of graphs drawn for different parameters. The numerical values of Nusselt number have been tabulated. The results of the study may be useful in the field related to the solar physics, the structure of rotating magnetic stars, rotating MHD induction machine energy generator and the sunspot development.

Keywords: MHD flow, inclined magnetic field, Hall current, rotation, radiation, natural convection.

1 Introduction

The unsteady MHD flow modeling has considerable role in the fluid dynamics. With the help of mathematical models many real life problems are analyzed and useful solutions are proposed. The model under consideration may be useful in the study of MHD generator, MHD pumps and accelerators, flow meters, planetary and solar plasma fluid dynamics systems, nuclear reactors using liquid metal coolants, rotating MHD induction machine energy generators etc. Convective heat transfer, often referred as convection, is the transfer of heat from one place to another by the movement of fluids. Convection is usually the dominant form of heat transfer in liquids and gases. Ali (1997) examined MHD-free convection from a vertical plate embedded in a thermally stratified porous medium with Hall effects. Singh A.K. et al (2019) have studied that analysis of mixed convection in water boundary layer flows over a moving vertical plate with variable viscosity and Prandtl number. Seth et al. (2009) have investigated MHD Couette flow in a rotating system in the presence of an inclined magnetic field. MHD flow over a moving plate in a rotating fluid with magnetic field, Hall currents and free stream velocity was studied by Takhar et al. (2002). Rajput and Kumar have investigated Radiation effect on MHD flow past an inclined plate with variable temperature and mass diffusion. Ghosh et al (2009) have studied Hall effect on MHD flow in a rotating system with heat transfer characteristics. Garg (2012) has worked on combined effects of thermal radiations and Hall current on moving vertical porous plate in a rotating system with variable temperature. Attia (2003) analyzed the effect of variable properties on unsteady Hartmann flow with heat transfer considering the Hall effect. Unsteady MHD flow past an impulsively started inclined plate with variable temperature and mass diffusion in the presence of Hall current was studied by Rajput and Kumar (2016). Hayat et al. (2004) studied Hall effects on unsteady hydromagnetic oscillatory flow of a second-grade fluid.

The present study is carried out to examine the Hall current and radiation effects on natural convection MHD flow in porous media along with a rotating system. The problem is solved by the Laplace transform method. Results of problem illustrating the effects of various parameters involved in the problem are presented and discussed. The numerical values of Nusselt number have been tabulated for the values of Prandtl number, time and radiation parameter.

2 Mathematical Analysis

The x - axis is taken along the vertical plane and z axis is normal to it. Thus the z - axis lies in the horizontal plane. The plate is taken along positive direction of x - axis. The fluid and the plate rotate as a rigid body with a uniform angular velocity Ω about z- axis. The fluid is permeated by uniform magnetic field B_0 which is imposed in the direction which makes an angle α with xz- plane. Fluid is taken electrically conducting whose magnetic Reynolds number is very small, therefore the induced magnetic field produced by the fluid motion is negligible in comparison to the applied one. Initially it is considered that the temperature of plate and fluid is T_∞ . Species concentration in the fluid is taken as C_∞. At time $t>0$, the plate starts moving with a velocity u_0 in its own plane, and temperature of the plate is raised to T_w and species concentration C_w of the plate vary linearly with time.

So, under above assumptions, the governing equations are as follows:

(2.1)
$$\frac{\partial u}{\partial t}-2\Omega \mathrm{v}=\upsilon\frac{\partial^2 u}{\partial z^2}+g\beta\ (T-T_\infty)+g\beta^*(C-C_\infty)-\frac{\sigma B_0^2 Cos^2\alpha}{\rho(1+m^2Cos^2\alpha)}(u+vmCos\alpha)-\frac{\upsilon u}{K}$$

(2.2)
$$\frac{\partial v}{\partial t}+2\Omega u=\upsilon\frac{\partial^2 v}{\partial z^2}-\frac{\sigma B_0^2 Cos^2\alpha}{\rho(1+m^2Cos^2\alpha)}(v-umCos\alpha)-\frac{\upsilon v}{K}$$

(2.3)
$$\rho C_p\frac{\partial T}{\partial t}=k\frac{\partial^2 T}{\partial z^2}-\frac{\partial q_r}{\partial z}$$

(2.4)
$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial z^2}$$

Equations (2.1) and (2.2) are called momentum equations. Equations (2.3) and (2.4) are known as energy equation and diffusion equation respectively.

The following initial and boundary conditions have been considered:

$$\mathrm{t}\le 0:\mathrm{u}=0,\ \ \mathrm{v}=0,\ \ \mathrm{T}=\mathrm{T}_\infty,\ \ \mathrm{C}=\mathrm{C}_\infty,\qquad \text{For each value of} z,$$

$$\mathrm{t}>0:u=u_0,\ \ v=0,\ \ T=T_\infty+(T_w-T_\infty)\frac{u_0^2t}{\upsilon}\ ,\ \ C=C_\infty+(C_w-C_\infty)\frac{u_0^2t}{\upsilon}\ ,at\ z{=}0,$$

$$(2.5)\ \mathrm{u}\to 0,\ \ \mathrm{v}\to 0,\ \ \mathrm{T}\to\mathrm{T}_\infty,\ \ \mathrm{C}\to\mathrm{C}_\infty as z\to\infty.$$

Here u, v are velocities of the fluid in x & z- directions, $g-$the acceleration due to gravity, $\beta-$volumetric coefficient of thermal expansion, β^*- volumetric coefficient of concentration expansion, t – time, $T-$the temperature of the fluid, $T_\infty-$fluid temperature in free stream, $C-$species concentration in the fluid, $C_\infty-$species concentration in free stream,$\upsilon-$ the kinematic viscosity, $\rho-$ the density, $C_P-$the specific heat at constant pressure, k – thermal conductivity of the fluid, D – molecular or mass diffusivity, $T_w-$the temperature in reference state, C_w-species concentration in reference state, B_0- the uniform magnetic field, $\sigma-$electrical conductivity,$K-$permeability of the porous medium, $\alpha-$angle of inclination from horizontal, Ω - angular velocity and m - The Hall current parameter.

The local radiant for the case of an optically thin gray gas is expressed as-

$$\frac{\partial q_r}{\partial z} = -4a^*\sigma^*(T_\infty^4 - T^4) \tag{2.6}$$

Where a^* is absorption constant and σ^* is Stefan Boltzmann constant.

The temperature difference within the flow is taken sufficiently small, so T^4can be expressed as the linear function of temperature. This is accomplished by expanding $T^4$from the Taylor series about $T_\infty$and neglecting higher-order terms.

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \tag{2.7}$$

Using the values of equations (2.6) and (2.7) in equation (2.3), we get-

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} - 16a^*\sigma^* T_\infty^3 (T - T_\infty) \tag{2.8}$$

To obtain equations in dimensionless form, we introduce the following non - dimensional quantities-

(2.9)

$$\bar{z} = \frac{zu_0}{\upsilon},\ \bar{u} = \frac{u}{u_0},\ \bar{v} = \frac{v}{u_0},\ \theta = \frac{(T-T_\infty)}{(T_w-T_\infty)},\ S_c = \frac{\upsilon}{D},\ P_r = \frac{\mu c_p}{k},\ R = \frac{16a^*\sigma^*\upsilon^2 T_\infty^3}{ku_0^2},$$
$$G_r = \frac{g\beta\upsilon(T_w-T_\infty)}{{u_0}^3},\ Ha^2 = \frac{\sigma B_0^2\upsilon}{\rho u_0^2},\ G_m = \frac{g\beta^*\upsilon(C_w-C_\infty)}{{u_0}^3},\ \bar{C} = \frac{(C-C_\infty)}{(C_w-C_\infty)},\ \bar{t} = \frac{tu_0^2}{\upsilon},$$
$$\bar{\Omega} = \frac{\upsilon\Omega}{u_0^2},\ \bar{K} = \frac{u_0}{\upsilon^2}K.$$

Where $\bar{u}, \bar{v}$ are dimensionless velocity in x & z-direction, R- radiation parameter, $\bar{t}-$ dimensionless time, Pr- Prandtl number, Sc- Schmidt number, Gr- thermal Grashof number, Gm- mass Grashof number, θ- dimensionless temperature, $\bar{C}$- dimensionless concentration, Ha- the Hartmann number, μ- the coefficient of viscosity, $\bar{\Omega}$ - dimensionless angular velocity, $\bar{K}-$permeability parameter and $\mu = \rho\upsilon$.

By using (2.9), the equations (2.1), (2.2), (2.8) and (2.4) become-

$$\frac{\partial\bar{u}}{\partial\bar{t}} - 2\bar{\Omega}\bar{v} = \frac{\partial^2\bar{u}}{\partial\bar{z}^2} + G_r\,\theta + G_m\,\bar{C} - \frac{Ha^2 Cos^2\alpha}{(1+m^2Cos^2\alpha)}(\bar{u} + \bar{v}mCos\alpha) - \frac{\bar{u}}{\bar{K}} \tag{2.10}$$

$$\frac{\partial\bar{v}}{\partial\bar{t}} + 2\bar{\Omega}\bar{u} = \frac{\partial^2\bar{u}}{\partial\bar{z}^2} - \frac{Ha^2 Cos^2\alpha}{(1+m^2Cos^2\alpha)}(\bar{v} - \bar{u}mCos\alpha) - \frac{\bar{v}}{\bar{K}} \tag{2.11}$$

$$\frac{\partial\theta}{\partial\bar{t}} = \frac{1}{P_r}\frac{\partial^2\theta}{\partial\bar{z}^2} - \frac{R\theta}{P_r} \tag{2.12}$$

$$\frac{\partial\bar{C}}{\partial\bar{t}} = \frac{1}{S_c}\frac{\partial^2\bar{C}}{\partial\bar{z}^2} \tag{2.13}$$

The corresponding conditions (2.5) become-

$$\begin{aligned}
&\mathrm{\bar{t}} \leq 0 : \mathrm{\bar{u}} = 0,\ \ \mathrm{\bar{v}} = 0,\ \ \theta = 0,\ \ \mathrm{\bar{C}} = 0,\ \text{ for every } \bar{z},\\
&\mathrm{\bar{t}} > 0 : \mathrm{\bar{u}} = 1,\ \ \mathrm{\bar{v}} = 0,\ \ \theta = \mathrm{\bar{t}},\ \ \mathrm{\bar{C}} = \mathrm{\bar{t}},\ \text{ at } \bar{z} = 0,\\
&\mathrm{\bar{u}} \to 0,\ \ \mathrm{\bar{v}} \to 0,\ \ \theta \to 0,\ \ \mathrm{\bar{C}} \to 0,\ \text{ as } \bar{z} \to \infty.
\end{aligned} \tag{2.14}$$

Dropping bars in the above equations, we get

$$\frac{\partial u}{\partial t} - 2\Omega v = \frac{\partial^2 u}{\partial z^2} + G_r\,\theta\ + G_m\,C\ - \frac{Ha^2Cos^2\alpha}{(1+m^2Cos^2\alpha)}(u + vmCos\alpha) - \frac{u}{K} \tag{2.15}$$

$$\frac{\partial v}{\partial t} + 2\Omega u = \frac{\partial^2 v}{\partial z^2} - \frac{Ha^2Cos^2\alpha}{(1+m^2Cos^2\alpha)}(v - umCos\alpha) - \frac{v}{K} \tag{2.16}$$

$$\frac{\partial\theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2\theta}{\partial z^2} - \frac{R\theta}{P_r} \tag{2.17}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial z^2} \tag{2.18}$$

The initial and boundary conditions become

$$\begin{aligned}
&\mathrm{t} \leq 0 : \mathrm{u} = 0,\ \mathrm{v} = 0,\ \theta = 0,\ \mathrm{C} = 0,\ \text{ for every } z,\\
&\mathrm{t} > 0 : \mathrm{u} = 1,\ \mathrm{v} = 0,\ \ \theta = \mathrm{t},\ \ \mathrm{C} = \mathrm{t},\ \text{ at } z{=}0,\\
&\mathrm{u} \to 0,\ \ \mathrm{v} \to 0,\ \ \theta \to 0,\ \ \mathrm{C} \to 0,\ \ \text{ as } z \to \infty.
\end{aligned} \tag{2.19}$$

To solve above system, take $\eta = u + iv$, then combining the equations (2.15) and (2.16), we get-

$$\frac{\partial\eta}{\partial \mathrm{t}} = \frac{\partial^2\eta}{\partial \mathrm{z}^2} + \mathrm{G_r}\,\theta\ + \mathrm{G_m}\,\mathrm{C}\ - \frac{Ha^2Cos^2\alpha}{1+m^2Cos^2\alpha}(1 - imCos\alpha)\eta - 2i\Omega\eta - \frac{\eta}{K} \tag{2.20}$$

$$\frac{\partial\theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2\theta}{\partial z^2} - \frac{R\theta}{P_r} \tag{2.21}$$

$$\frac{\partial C}{\partial t}=\frac{1}{S_c}\frac{\partial^2 C}{\partial z^2} \tag{2.22}$$

The corresponding initial and boundary conditions are-

$$\begin{aligned}&\mathrm{t}\le 0:\eta=0,\ \theta=0,\ \mathrm{C}=0,\ \text{for all}\ \ z,\\&\mathrm{t}>0:\eta=1,\ \theta=\mathrm{t},\ \mathrm{C}=\mathrm{t},\ \text{at}\ \ z=0,\\&\eta\to 0,\ \ \theta\to 0,\ \ \mathrm{C}\to 0,\ \ \text{as}\ \ z\to\infty.\end{aligned} \tag{2.23}$$

The dimensionless governing equations (2.20) to (2.22), subject to the conditions (2.23), are solved by Laplace - transform method. The solution obtained is as under:

$$\begin{aligned}\eta=&\tfrac{1}{4\zeta^2}G_r[2e^{-\sqrt{a}z}(A_1+P_rA_2)-zA_3e^{-\sqrt{a}z}(\tfrac{R}{\sqrt{a}}-\sqrt{a})+2tA_2e^{-\sqrt{a}z}\zeta+2\chi A_{12}A_4]+\tfrac{1}{2}e^{-\sqrt{a}z}A_{33}\\&+\tfrac{1}{4a^2}G_m[e^{-\sqrt{a}z}(2A_1+2\sqrt{a}A_3)+2e^{-\sqrt{a}z}A_2(S_c+at)+2A_{13}A_5(1\ -S_c)]-\tfrac{1}{2\zeta^2A_{11}}P_rG_r[\chi A_{14}A_7z\\&+A_{16}A_6z\{\ t\zeta-\chi\}+\tfrac{1}{2}\sqrt{\tfrac{P_r}{R}}A_{16}A_8A_{11}z\zeta]\ -\tfrac{G_m}{2a^2\sqrt{\pi}}[2az\sqrt{S_c}e^{-\frac{z^2S_c}{4t}}\sqrt{t}+A_{15}\sqrt{\pi}(az^2S_c\\&+2at+2S_c-2)\ +A_{13}\sqrt{\pi}(A_9+A_{10}S_c)]\end{aligned}$$

$$\theta=\frac{1}{4\sqrt{\mathrm{R}}}\mathrm{e}^{-\sqrt{\mathrm{R}}z}\{\mathrm{e}^{2\sqrt{\mathrm{R}}z}erfc[\frac{2\sqrt{\mathrm{R}}t+z\mathrm{P_r}}{2\sqrt{\mathrm{P_r t}}}](2\sqrt{\mathrm{R}}t+z\mathrm{P_r})+erfc[\frac{-2\sqrt{\mathrm{R}}t+z\mathrm{P_r}}{2\sqrt{\mathrm{P_r t}}}](2\sqrt{\mathrm{R}}t-z\mathrm{P_r})\}$$

$$C=t(1+\frac{z^2S_c}{2t})erfc[\frac{\sqrt{S_c}}{2\sqrt{t}}]-t\frac{z\sqrt{S_c}}{\sqrt{\pi}\sqrt{t}}e^{-\frac{z^2}{4t}}S_c$$

The expressions for the symbols involved in the above equations are given in the appendix.

Nusselt number

The dimensionless Nusselt number is given by the formula-

$$Nu=-\left(\frac{\partial\theta}{\partial z}\right)_{z=0}=\frac{e^{-\frac{Rt}{P_r}}\sqrt{tP_r}}{\sqrt{\pi}}-erfc[\frac{\sqrt{R}t}{\sqrt{tP_r}}](\sqrt{R}t-\frac{\sqrt{R}}{2}t+\frac{P_r}{4\sqrt{R}})+erfc[-\frac{\sqrt{R}t}{\sqrt{tP_r}}](\frac{\sqrt{R}}{2}t+\frac{P_r}{4\sqrt{R}})$$

The numerical values of Nusselt number for different parameters are shown in table-1.

3 Results and Discussion

In the present paper we have studied the rotation and radiation effects on unsteady free convection MHD flow in the presence of Hall current and an inclined magnetic field. The analytical results of primary velocity u and secondary velocity v are shown graphically in figures 1 to 6 and the numerical values of Nusselt number are tabulated in table-1. It is evident from figures 1 and 3 that the primary velocity u and secondary velocity v increase on increasing either αor m. It is also clear from figures 5 and 6 that the primary velocity u and secondary velocity v increase on increasing the value of R and K. This implies that the inclination of magnetic field, Hall current, permeability parameter and radiation tend to accelerate fluid velocity in both the primary and the secondary flow directions. From figure 2, it is clear that the primary velocity u and secondary velocity v decrease on increasing Ha

which shows that magnetic field has retarding influence on the fluid velocity in both the primary and the secondary flow directions. Effect of rotation on fluid flow is shown by figure 4. It is observed that an increase in rotation parameter Ω primary velocity decreases throughout the boundary layer region whereas secondary velocity increases continuously near the surface of the plate. This implies that rotation tends to accelerate secondary velocity whereas it retards primary velocity in the boundary layer region.

The numerical values of Nusselt number are given in table-1. It is seen that the value of Nuincreases with increase in Prandtl number, radiation parameter and time.

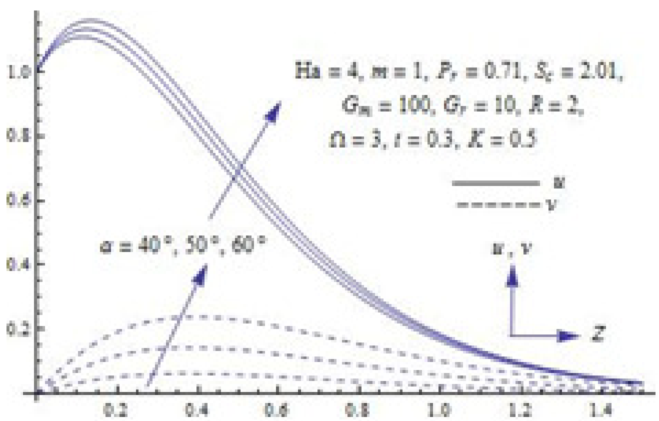

Fig. 1: Primary and secondary velocity profile for different values of α

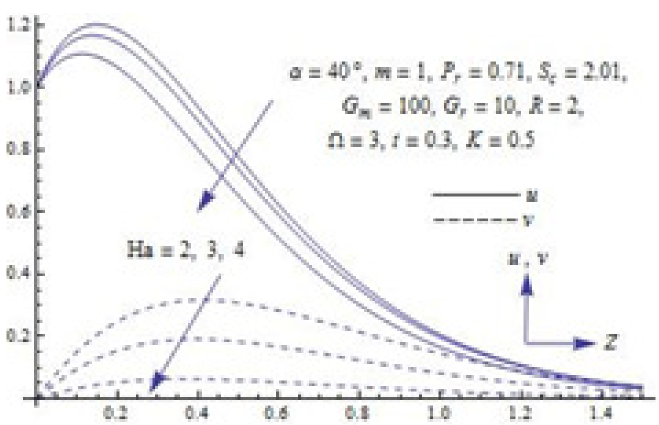

Fig. 2: Primary and secondary velocity profile for different values of H_a

Table 1: Nusselt number for different parameters

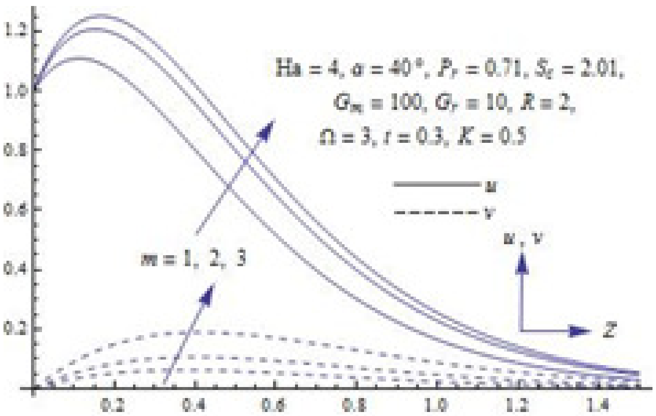

Fig. 3: Primary and secondary velocity profile for different values of m

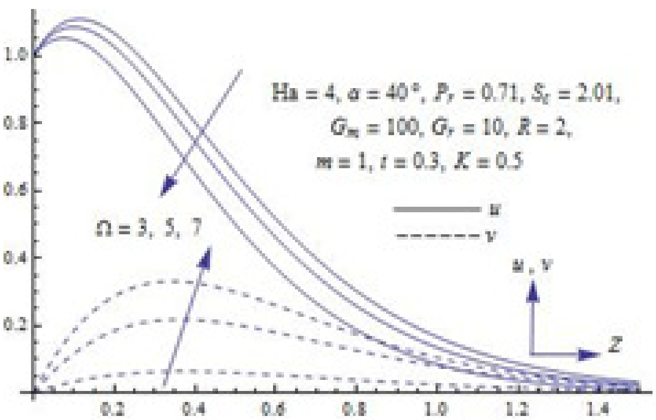

Fig. 4: Primary and secondary velocity profile for different values of Ω

P_r	R	t	Nu
0.71	2	0.30	0.65640
7.00	2	0.30	1.68150
0.71	7	0.30	0.92750
0.71	10	0.30	1.06088
0.71	2	0.20	0.50089
0.71	2	0.25	0.57985

4 Conclusion

A theoretical analysis has been done to study the Hall current and radiation effects on natural convection MHD flow in porous media along with a rotating system and an inclined magnetic field. It is found that the magnetic field, inclination of magnetic field, Hall current, radiation and rotation have significant effects in fluid

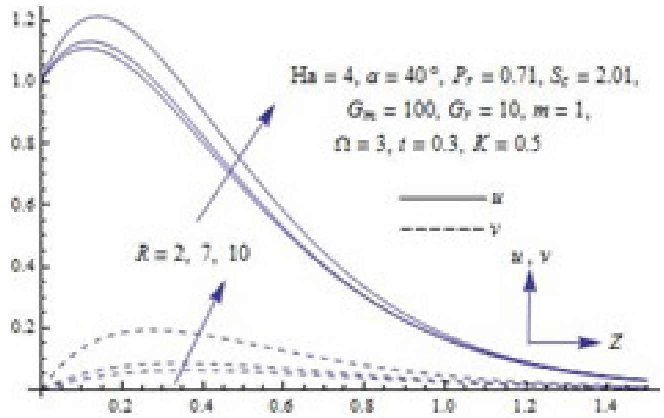

Fig. 5: Primary and secondary velocity profile for different values of R

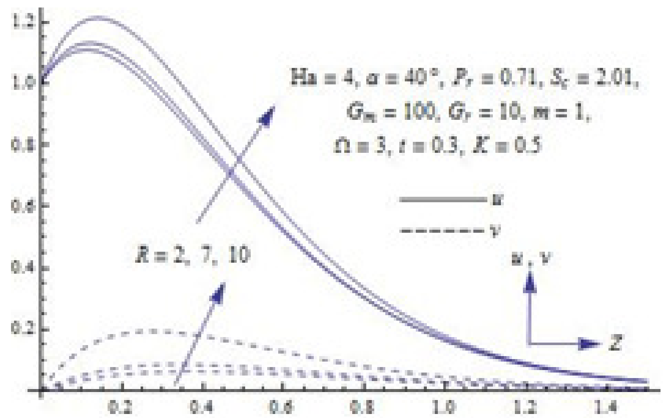

Fig. 6: Primary and secondary velocity profile for different values of K

flow. Inclination of magnetic field and Hall current tend to accelerate fluid velocity in both the primary and the secondary flow directions. Magnetic field has retarding influence. It has been found that the velocity in the boundary layer region increases with increasing the values of radiation parameter. It is also observed that radiation and rotation parameters increase the drag at the plate surface. The value of Nu increases with increase in Prandtl number, radiation parameter and time.

Appendix

$$a = \frac{M(1-im)}{1+m^2} + 2i\Omega + \frac{1}{K}, \chi = 1 - P_r \zeta = a - R, A_0 = \frac{u_0^2 t}{\upsilon}, A_1 = 1 + e^{2\sqrt{a}z}(1$$
$$-A_{18}) - A_{17}, A_2 = -A_1, A_3 = 1 - e^{2\sqrt{a}z}(1 - A_{18}) - A_{17}, A_4 = -1 + A_{19} + A_{30}(A_{20} - 1),$$
$$A_5 = -1 + A_{21} + A_{28}(A_{22} - 1), A_6 = -1 + A_{23} + A_{26}(A_{31} - 1), A_7 = -1 + A_{29}$$
$$+A_{27}(A_{30} - 1), A_8 = -1 + A_{23} + A_{26}(A_{31} - 1), A_9 = -1 - A_{24} - A_{28}(1 - A_{25}),$$
$$A_{10} = -A_9, A_{11} = Abs[z].Abs[P_r], A_{12} = e^{\frac{at}{P_r-1} - \frac{Rt}{P_r-1} - z\sqrt{\frac{aP_r-R}{P_r-1}}}, A_{13} = e^{\frac{at}{S_c-1} - z\sqrt{\frac{aS_c}{S_c-1}}},$$
$$A_{14} = e^{\frac{at}{P_r-1} - \frac{Rt}{P_r-1} - Abs[z]\sqrt{\frac{P_r(aP_r-R)}{P_r-1}}}, A_{15} = -1 + erf[\frac{z\sqrt{S_c}}{2\sqrt{t}}], A_{16} = e^{Abs[z]\sqrt{P_r R}},$$
$$A_{17} = erf[\frac{2\sqrt{a}t - z}{2\sqrt{t}}], A_{18} = erf[\frac{2\sqrt{a}t + z}{2\sqrt{t}}], A_{19} = erf[\frac{z - 2t\sqrt{\frac{aP_r-R}{P_r-1}}}{2t}],$$
$$A_{20} = erf[\frac{z + 2t\sqrt{\frac{aP_r-R}{P_r-1}}}{2t}], A_{21} = erf[\frac{z - 2t\sqrt{\frac{aS_c}{S_c-1}}}{2t}], A_{22} = erf[\frac{z + 2t\sqrt{\frac{aS_c}{S_c-1}}}{2t}],$$
$$A_{23} = erf[\frac{Abs[z].Abs[P_r]}{2\sqrt{t}} - \sqrt{\frac{tR}{P_r}}], A_{24} = erf[\frac{2t\sqrt{\frac{a}{S_c-1}} - 2\sqrt{S_c}}{2t}], A_{25} = erf[\frac{2t\sqrt{\frac{a}{S_c-1}} + 2\sqrt{S_c}}{2t}],$$
$$A_{16} = e^{Abs[z]\sqrt{P_r R}}, A_{27} = e^{2Abs[z]\sqrt{\frac{P_r(aP_r-R)}{P_r-1}}}, A_{28} = e^{-2z\sqrt{\frac{aS_c}{S_c-1}}}, A_{29} = erf[\frac{Abs[z].Abs[P_r]}{2\sqrt{t}}$$
$$-\sqrt{\frac{t(R-aP_r)}{P_r(1-P_r)}}], A_{30} = e^{-2z\sqrt{\frac{aP_r-R}{P_r-1}}}, A_{31} = erf[\frac{Abs[z].Abs[P_r]}{2\sqrt{t}} + \sqrt{\frac{tR}{P_r}}], A_{32} = erf[\frac{Abs[z].Abs[P_r]}{2\sqrt{t}}$$
$$+\sqrt{\frac{t(R-aP_r)}{P_r(1-P_r)}}], A_{33} = 1 + A_{17} + e^{2\sqrt{a}z} A_{34}, A_{34} = erfc[\frac{2\sqrt{a}t + z}{2\sqrt{t}}],$$

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