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Rotational and Hall Current Effects on a Free Convection MHD Flow with Radiation and Inclined Magnetic Field

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Abstract

Rotational and Hall current effects on a free convection MHD flow with Radiation and inclined magnetic field are studied here. Electrically conducting, viscous, and incompressible fluid is taken. The flow is modelled with the help of partial differential equations. The analytical solutions for the velocity, concentration, and temperature are solved by the Laplace integral transform method. The outcomes acquired have been examined with the help of graphs drawn for different parameters like Hartmann number, Hall current parameter, inclination of magnetic field, angular velocity and radiation parameter, etc. The variation of the Nusselt number has been shown graphically. It is observed that Hall current parameter and inclination of magnetic field reduces the resistive effect of the applied external magnetic field. Such a study assumes importance because both rotation and Hall current induce secondary flow in the flow-field. The conclusion of the study may be useful in the field of solar physics, rotating magnetic stars, rotating MHD induction machine energy generator and many industrial applications.

Keywords: MHD; Hall current; Radiation; Rotation; Free convection; Majic field; Mass transfer; Nusselt number

MSC 2010 No.: 76W05, 76D05, 80A20

1. Introduction

The unsteady rotational MHD flow with convective heat transfer has considerable role in the fluid dynamics. With the help of mathematical models many real life problems are analysed and useful solutions are obtained. The model under consideration may be useful in the study of MHD generator, MHD accelerators and pumps, flow meters, planetary and solar plasma fluid dynamics systems, nuclear reactors using liquid metal coolants, rotating MHD induction machine energy generators etc. Agrawal et al. (1983) studied combined effect of dissipation and Hall effect on free convective in a rotating fluid. Hayat et al. (2004) obtained a solution of Hall effects on unsteady hydromagnetic oscillatory flow of a second-grade fluid. 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. Kumar et al. (2019) found the chemical reaction effect on MHD flow past an impulsively started vertical cylinder with variable temperature and mass diffusion.

Seth et al. (2009) have investigated MHD couette flow in a rotating system in the presence of an inclined magnetic field. Masthanrao et al. (2013) presented chemical reaction and Hall effects on MHD convective flow along an infinite vertical porous plate with variable suction and heat absorption. Ghosh et al. (2009) have studied Hall effect on MHD flow in a rotating system with heat transfer characteristics. 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). Kumar and Bansal (2019) studied unsteady flow past on vertical cylinder in the presence of an inclined magnetic field and chemical reaction. Attia (2003) analyzed the effect of variable properties on unsteady Hartmann flow with heat transfer considering the Hall effect. Rajput and Kumar (2017) have investigated Radiation effect on MHD flow past an inclined plate with variable temperature and mass diffusion. Singh 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.

Effect of porosity on unsteady MHD convection flow past a moving vertical plate with ramped wall temperature was studied by Rajput and Shareef (2020). Beg et al. (2009) found numerical study of free convection magnetohydrodynamic heat and mass transfer from a stretching surface to a saturated porous medium with Soret and Dufour effects. Seth et al. (2010) investigated unsteady hydromagnetic couette flow within porous plates in a rotating system. Dufour effect on free convection MHD flow past an impulsively started vertical oscillating plate through porous media with variable temperature and constant mass diffusion is studied by Rajput and Gupta (2016). Mythreye et al. (2015) discovered the chemical reaction on unsteady MHD convective heat and mass transfer past a semi-infinite vertical permeable moving plate with heat absorption. Hall effects on unsteady MHD Free convection flow over a stretching sheet with variable viscosity and viscous dissipation are studied by Maripala and Naikoti (2015). Jagdish Prakash et al. (2014) presented the Radiation and Dufour Effects on unsteady MHD mixed convective flow in an accelerated vertical wavy plate with varying temperature and mass diffusion. Sheikholeslami (2017) performed magnetic field influence on nano fluid thermal radiation in a cavity with tilted elliptic inner cylinder. Jacob et al. (2012) worked on magnetic field and Hall current effect on MHD free convection flow past a vertical rotating flat plate. Muthuraj et al. (2016) found the influences of chemical reaction and wall properties on MHD peristaltic transport of a dusty fluid with heat and mass transfer. Radiation effects on MHD stagnation-point flow of a nanofluid over an exponentially stretching sheet have been investigated by Imran et al. (2014).

The current investigation is completed to inspect the Rotational and Hall current effects on a free convection MHD flow with Radiation and inclined magnetic field. The problem is solved by using the Laplace integral transform method. Results of problem describing the impacts of different parameters engaged with the issue are discussed and presented.

2. Mathematical Analysis

The electrically conducting, incompressible, and viscous fluid is chosen, whose magnetic Reynolds number is minuscule. Thus, the induced magnetic field generated by the motion of fluid is negligible as compared to the applied external magnetic field. Heat is transferred through free convection. The z-axis is chosen along the horizontal plane and x-axis is normal to it. Thus the x-axis lies in the vertical plane. The plate is taken along positive direction of x-axis. The fluid and the plate revolve as a stiff body about z-axis with a constant angular velocity Ω. The fluid is penetrated by uniform external magnetic field B_0 which is imposed in the direction whose inclination is α with xz-plane. Initially, it is expected to be that the temperature of fluid and plate is T_∞. Concentration of species in the fluid is chosen as C_∞. At time $t>0$, the plate begins moving with a velocity u_0 in its own plane, and temperature of the plate is increased to T_w and species concentration C_w of the plate vary linearly with respect to time.

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

Momentum equations:

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

and

$$\frac{\partial v}{\partial t}+2u\Omega=\upsilon\frac{\partial^2 v}{\partial z^2}-\frac{\sigma B_0^2\mathrm{Cos}^2\alpha}{\rho(1+m^2\mathrm{Cos}^2\alpha)}(v-um\mathrm{Cos}\alpha). \tag{2}$$

Energy equation:

$$\rho C_p\frac{\partial T}{\partial t}=k\frac{\partial^2 T}{\partial z^2}-\frac{\partial q_r}{\partial z}. \tag{3}$$

Diffusion equation:

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial z^2}. \tag{4}$$

Equations (1) and (2) are called momentum equations. Equation (3) and (4) are known as the energy equation and diffusion equation, respectively.

The following boundary conditions have been considered.

$$\begin{cases} t \le 0: \ u = 0, v = 0, T = T_\infty, C = C_\infty, \\ t > 0: \ u = u_0, v = 0, T = T_\infty + (T_w - T_\infty)\dfrac{u_0^2 t}{\upsilon}, C = C_\infty + (C_w - C_\infty)\dfrac{u_0^2 t}{\upsilon}, \text{ at } z = 0, \end{cases} \tag{5}$$

$$u \to 0,\ v \to 0,\ T \to T_\infty,\ C \to C_\infty \text{ as } z \to \infty.$$

The value of local radiant for optically thin gray gas is communicated as:

$$\frac{\partial q_r}{\partial z} = -4a^* \sigma^* (T_\infty^4 - T^4). \tag{6}$$

The temperature difference in the flow is picked adequately little, so expanding T^4 from the Taylor series about T_∞ as the linear function of temperature (neglecting higher-order terms),

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4. \tag{7}$$

Put the values of $\frac{\partial q_r}{\partial z}$ from Equation (6) and T^4 from Equation (7) in Equation (3), we get,

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} - 16a^* \sigma^* T_\infty^3 (T - T_\infty). \tag{8}$$

To obtain Equations in dimensionless from, we introduce the following non-dimensional quantities,

$$\left.\begin{aligned} &\bar{z} = \frac{z u_0}{\upsilon},\ \bar{u} = \frac{u}{u_0},\ \bar{v} = \frac{v}{u_0},\ \theta = \frac{(T - T_\infty)}{(T_w - T_\infty)},\ S_c = \frac{\upsilon}{D},\ \mu = \rho\upsilon,\ R = \frac{16a^*\sigma^*\upsilon^2 T_\infty^3}{k u_0^2}, \\ &G_r = \frac{g\upsilon\beta(T_w - T_\infty)}{u_0^{\ 3}},\ Ha^2 = \frac{\sigma B_0^2 \upsilon}{\rho u_0^2},\ G_m = \frac{g\beta^*\upsilon(C_w - C_\infty)}{u_0^{\ 3}},\ \overline{C} = \frac{(C - C_\infty)}{(C_w - C_\infty)}, \\ &\overline{\Omega} = \frac{\upsilon\Omega}{u_0^2}, P_r = \frac{\mu c_p}{k}, \bar{t} = \frac{t u_0^2}{\upsilon}. \end{aligned}\right\} \tag{9}$$

By using (9), the Equations (1), (2), (8) and (4) become:

$$\frac{\partial \bar{u}}{\partial \bar{t}} - 2\overline{\Omega}\bar{v} = \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} - \frac{Ha^2 \mathrm{Cos}^2\alpha}{(1 + m^2 \mathrm{Cos}^2\alpha)}(\bar{u} + \bar{v} m \mathrm{Cos}\alpha) + G_r\,\theta + G_m\,\overline{C}\,, \tag{10}$$

$$\frac{\partial \bar{v}}{\partial \bar{t}} + 2\overline{\Omega}\bar{u} = \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} - \frac{Ha^2 \mathrm{Cos}^2\alpha}{(1 + m^2 \mathrm{Cos}^2\alpha)}(\bar{v} - \bar{u} m \mathrm{Cos}\alpha), \tag{11}$$

$$\frac{\partial\theta}{\partial\bar{t}} = \frac{1}{P_r}\frac{\partial^2\theta}{\partial\bar{z}^2} - \frac{R\theta}{P_r}, \tag{12}$$

$$\frac{\partial\overline{C}}{\partial\bar{t}} = \frac{1}{S_c}\frac{\partial^2\overline{C}}{\partial\bar{z}^2}. \tag{13}$$

The corresponding boundary conditions (5) become:

$$\left.\begin{array}{l}\bar{t}\le 0{:}\,\bar{u}=0,\ \ \bar{v}=0,\ \ \theta=0,\ \ \overline{C}=0,\ \text{for every}\ \bar{z}\,,\\ \bar{t}>0{:}\,\bar{u}=1,\ \ \bar{v}=0,\ \ \theta=\bar{t},\ \ \overline{C}=\bar{t},\ \ \text{at}\ \ \bar{z}=0,\\ \bar{u}\to 0,\ \ \bar{v}\to 0,\ \ \theta\to 0,\ \ \overline{C}\to 0,\ \ \text{as}\ \ z\to\infty.\end{array}\right\} \tag{14}$$

Dropping bars in the above Equations, we get:

$$\frac{\partial u}{\partial t} - 2\Omega v = \frac{\partial^2 u}{\partial z^2} + G_r\,\theta + G_m\,C - \frac{Ha^2\text{Cos}^2\alpha}{(1+m^2\text{Cos}^2\alpha)}(u+vm\text{Cos}\alpha), \tag{15}$$

$$\frac{\partial v}{\partial t} + 2\Omega u = \frac{\partial^2 v}{\partial z^2} - \frac{Ha^2\text{Cos}^2\alpha}{(1+m^2\text{Cos}^2\alpha)}(v-um\text{Cos}\alpha), \tag{16}$$

$$\frac{\partial\theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2\theta}{\partial z^2} - \frac{R\theta}{P_r}, \tag{17}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial z^2}. \tag{18}$$

The corresponding boundary conditions are:

$$\left.\begin{array}{l}t\le 0{:}\,u=0,\ v=0,\ \theta=0,\ C=0,\ \text{for every}\ z,\\ t>0{:}\,u=1,\ v=0,\ \ \theta=t,\ \ C=t,\ \text{at}\ z=0,\\ u\to 0,\ \ v\to 0,\ \ \theta\to 0,\ \ C\to 0,\ \text{as}\ z\to\infty\,.\end{array}\right\} \tag{19}$$

To solve above system, take $\eta = u + iv$. Combining the Equations (15) and (16), we get:

$$\frac{\partial\eta}{\partial\text{t}} = \frac{\partial^2\eta}{\partial\text{z}^2} - \frac{Ha^2\text{Cos}^2\alpha}{1+m^2\text{Cos}^2\alpha}(1-im\text{Cos}\alpha)\eta + G_r\,\theta + G_m\,C - 2i\Omega\eta, \tag{20}$$

$$\frac{\partial\theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2\theta}{\partial z^2} - \frac{R\theta}{P_r}, \tag{21}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial z^2}. \tag{22}$$

The corresponding boundary conditions become:

$$\left.\begin{array}{l} t \le 0: \eta = 0,\ \theta = 0,\ C = 0, \text{ for all } z, \\ t > 0: \eta = 1,\ \theta = t,\ C = t, \text{ at } z = 0, \\ \eta \to 0,\ \theta \to 0,\ C \to 0, \text{ as } z \to \infty. \end{array}\right\} \quad (23)$$

The dimensionless above equations (20) to (22), with conditions (23), are solved by Laplace – integral transform method. The solution obtained for $\eta, \theta,$ and C is as follows:

$$\begin{aligned} \eta = {} & \frac{1}{2\zeta^2 A_{11}} P_r G_r [A_{16} A_6 z\{\chi - t\zeta\} - \chi A_{14} A_7 z - \frac{1}{2}\sqrt{\frac{P_r}{R}} A_{16} A_8 A_{11} z\zeta] + \frac{1}{2} e^{-\sqrt{a}z} A_{33} \\ & + \frac{1}{4\zeta^2} G_r [2e^{-\sqrt{a}z}(A_1 + P_r A_2) - zA_3 e^{-\sqrt{a}z}(\frac{R}{\sqrt{a}} - \sqrt{a}) + 2tA_2 e^{-\sqrt{a}z}\zeta + 2\chi A_{12} A_4] \\ & + \frac{1}{4a^2} G_m [e^{-\sqrt{a}z}(2A_1 + 2\sqrt{a}A_3) + 2e^{-\sqrt{a}z} A_2 (S_c + at) + 2A_{13} A_5 (1 - S_c)] \\ & - \frac{G_m}{2a^2\sqrt{\pi}} [2az\sqrt{S_c} e^{-\frac{z^2 S_c}{4t}} \sqrt{t} + A_{15}\sqrt{\pi}(az^2 S_c + 2at + 2S_c - 2) + A_{13}\sqrt{\pi}(A_9 + A_{10} S_c)], \end{aligned} \quad (24)$$

$$\theta = \frac{1}{4\sqrt{R}} \{e^{2\sqrt{R}z} erfc[\frac{2\sqrt{R}t + zP_r}{2\sqrt{P_r t}}](2\sqrt{R}t + zP_r) + erfc[\frac{-2\sqrt{R}t + zP_r}{2\sqrt{P_r t}}](2\sqrt{R}t - zP_r)\} e^{-\sqrt{R}z}, \quad (25)$$

$$C = t(1 + \frac{z^2 S_c}{2t}) erfc[\frac{\sqrt{S_c}}{2\sqrt{t}}] - t\frac{z\sqrt{S_c}}{\sqrt{\pi}\sqrt{t}} e^{-\frac{z^2}{4t}} S_c. \quad (26)$$

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

2.1. Nusselt number

The dimensionless Nusselt number is calculated by the formula:

$$Nu = -\left(\frac{\partial\theta}{\partial z}\right)_{z=0}.$$

The graphical estimation of Nusselt number is shown in Figure 6 for different parameters.

3. Result and Discussions

In the present manuscript, we have studied the Rotational and Hall current effects on a free convection MHD flow in the presence of Radiation and inclined magnetic field. The logical aftereffects of primary velocity u and secondary velocity v are shown graphically in Figures 1 to 5 and the graphical variation of Nusselt number are given in Figure 6. It is evident from Figures 1 and 3 that the velocity u in x-axis and velocity v in z-axis increase on increasing either α or m, i.e., it reduces the resistive effect of the applied magnetic field. It is also found from Figure 5 that u

and v increase on increasing the value of R. This implies that the inclination of magnetic field (α), radiation (R), and Hall current (m) tend to boost 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. Rotational effect on fluid flow is appeared in Figure 4. It is detect that on increasing rotation parameter Ω, primary velocity u decreases throughout the boundary layer region whereas secondary velocity v increases permanently near the surface of the plate which infers that rotation tends to speed up of secondary velocity whereas it speed down of primary velocity in the boundary layer region.

The graph of Nusselt number with respect to time for different parameters is obtained in Figure 6. It is seen that the value of Nu increases with increase in Prandtl number and radiation parameter with respect to time.

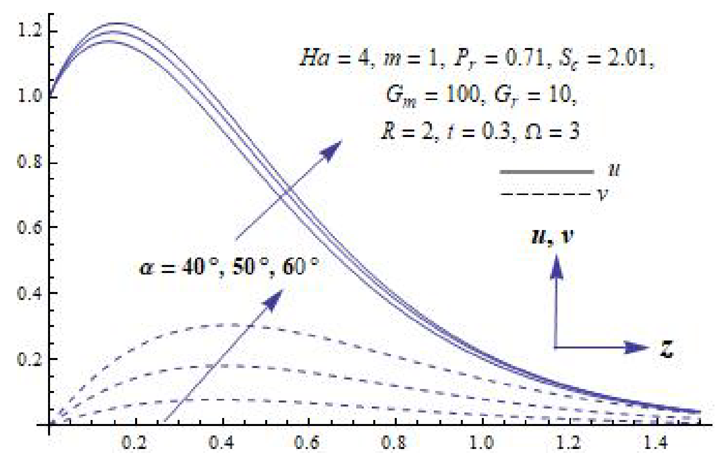

Figure 1. Primary and secondary velocity profile for different values of α

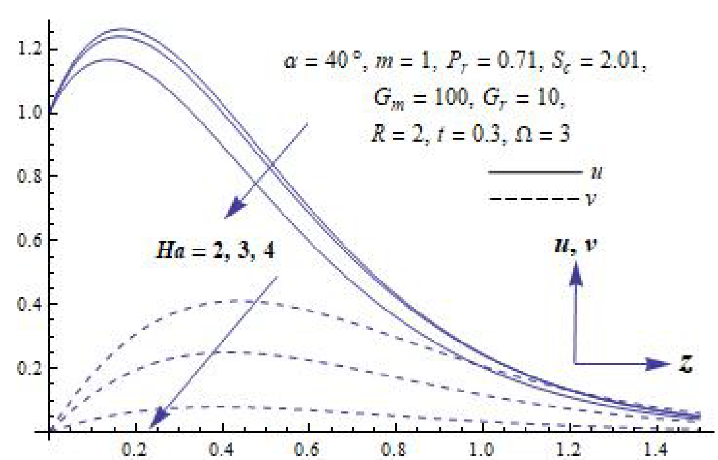

Figure 2. Primary and secondary velocity profile for different values of H_a

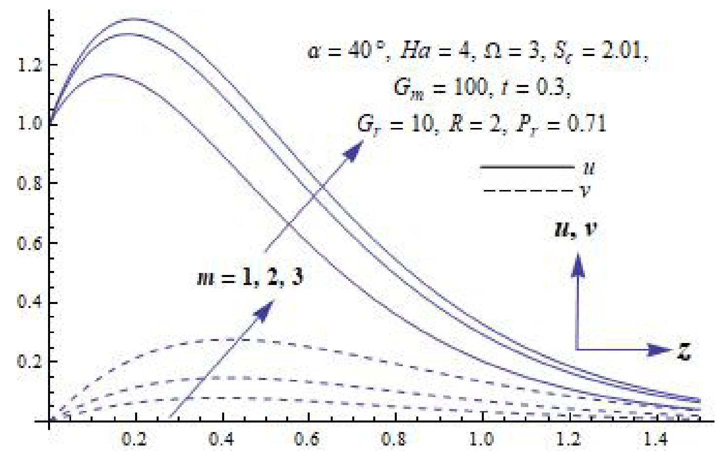

Figure 3. Primary and secondary velocity profile for different values of *m*

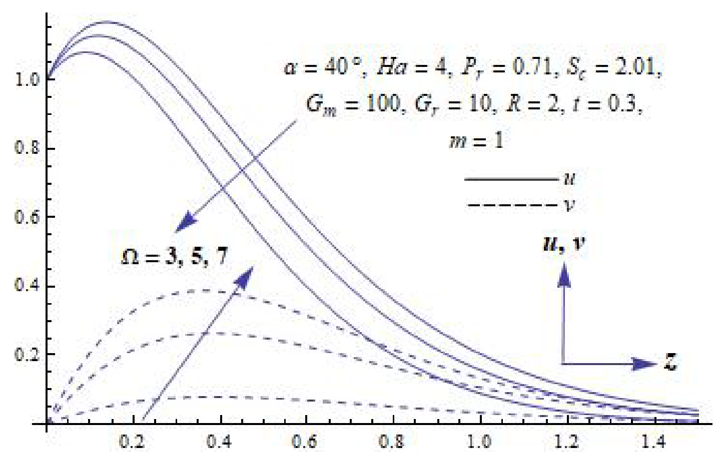

Figure 4. Primary and secondary velocity profile for different values of Ω

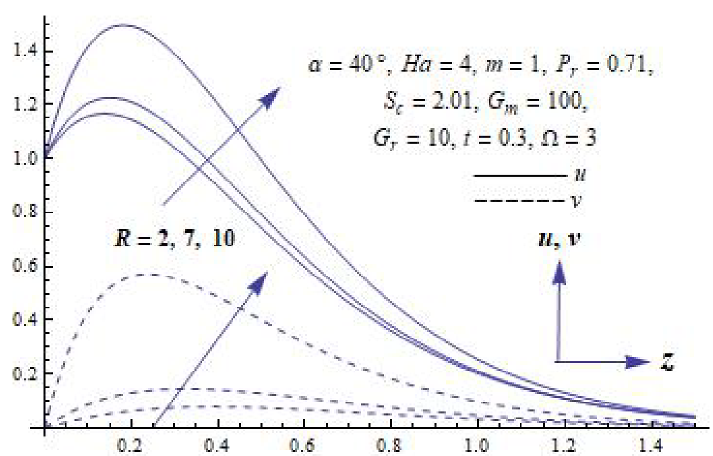

Figure 5. Primary and secondary velocity profile for different values of *R*

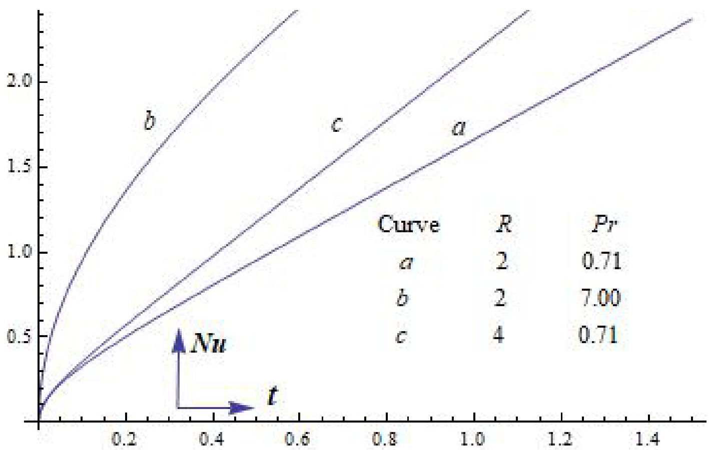

Figure 6. Nusselt number profile with time

4. Conclusion

A theoretical analysis of Rotational and Hall current effects on a free convection MHD flow with Radiation and inclined magnetic field is investigated. It is discovered that the magnetic field, inclination of magnetic field, Hall current, radiation and rotation have significant effects in fluid flow. Inclination of magnetic field and Hall current tend to boost the fluid velocity in both the primary and the secondary flow directions. External magnetic field has retarding influence on both directions of velocities. It has been found from increase the values of radiation parameter, the velocity in the boundary layer region increases. It is also observed that radiation and rotation parameters increase the drag at the plate surface.

The value of *Nu* increases with increase in radiation parameter and Prandtl number with respect to time.

The results of this study may be applicable in the field related to the solar physics dealing with the solar cycle, MHD sensors, rotating MHD induction machine, energy generator, the sunspot development, the structure of rotating magnetic stars, etc.

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Appendix

$$a=\frac{M(1-im)}{1+m^2}+2i\Omega,\ \chi=1-P_r,\ \zeta=a-R,\ A_0=\frac{u_0^2t}{\upsilon},\ A_1=1+e^{2\sqrt{az}}(1-A_{18})-A_{17},$$

$$A_2=-A_1,\ A_3=1-e^{2\sqrt{az}}(1-A_{18})-A_{17},\ A_4=-1+A_{19}+A_{30}(A_{20}-1),\ A_5=-1+A_{21}+A_{28}(A_{22}-1),$$

$$A_6=-1+A_{23}-A_{26}(1-A_{31}),\ A_7=-1++A_{27}(A_{30}-1)A_{29},\ A_8=-1+A_{23}+A_{26}(A_{31}-1),$$

$$A_9=-1-A_{24}-A_{28}(1-A_{25}),\ A_{10}=-A_9,\ A_{11}=Abs[P_r]Abs[z],\ A_{12}=e^{\frac{at}{P_r-1}-\frac{Rt}{P_r-1}-z\sqrt{\frac{aP_r-R}{P_r-1}}},$$

$$A_{13}=e^{\frac{at}{S_c-1}-z\sqrt{\frac{aS_c}{S_c-1}}},\ A_{14}=e^{\frac{at}{P_r-1}-\frac{Rt}{P_r-1}-Abs[z]\sqrt{\frac{P_r(aP_r-R)}{P_r-1}}},\ A_{15}=-1+erf[\frac{z\sqrt{S_c}}{2\sqrt{t}}],\quad A_{16}=e^{Abs[z]\sqrt{P_rR}},$$

$$A_{17}=erf[\frac{2t\sqrt{a}-z}{2\sqrt{t}}],\ A_{18}=erf[\frac{2t\sqrt{a}+z}{2\sqrt{t}}],\ A_{19}=erf[\frac{z-2\sqrt{\frac{aP_r-R}{P_r-1}}t}{2t}],$$

$$A_{20}=erf[\frac{z+2t\sqrt{\frac{aP_r-R}{P_r-1}}}{2t}],\ A_{21}=erf[\frac{z-2t\sqrt{\frac{aS_c}{S_c-1}}}{2t}],\ A_{22}=erf[\frac{z+2t\sqrt{\frac{aS_c}{S_c-1}}}{2t}],$$

$$A_{23}=erf[\frac{Abs[z].Abs[P_r]}{2\sqrt{t}}-\sqrt{\frac{tR}{P_r}}],\ A_{24}=erf[\frac{2t\sqrt{\frac{a}{S_c-1}}-2\sqrt{S_c}}{2t}],\ A_{25}=erf[\frac{2t\sqrt{\frac{a}{S_c-1}}+2\sqrt{S_c}}{2t}],$$

$$A_{26}=e^{2Abs[z]\sqrt{P_rR}},\ A_{27}=e^{2Abs[z]\sqrt{\frac{P_r(aP_r-R)}{P_r-1}}},\ A_{28}=e^{-2z\sqrt{\frac{aS_c}{S_c-1}}},\ A_{29}=erf[\frac{Abs[z].Abs[P_r]}{2\sqrt{t}}-\sqrt{\frac{t(R-aP_r)}{P_r(1-P_r)}}],$$

$$A_{30} = e^{-2z\sqrt{\frac{aP_r - R}{P_r - 1}}}, \; A_{31} = erf[\frac{Abs[z].Abs[P_r]}{2\sqrt{t}} + \sqrt{\frac{tR}{P_r}}], \; A_{32} = erf[\frac{Abs[z].Abs[P_r]}{2\sqrt{t}} + \sqrt{\frac{t(R - aP_r)}{P_r(1-P_r)}}],$$

$$A_{33} = 1 + A_{17} + e^{2\sqrt{a}z} A_{34}, \; A_{34} = erfc[\frac{2\sqrt{a}t + z}{2\sqrt{t}}].$$

Nomenclature

a^* absorption constant
t time
β volumetric coefficient of thermal expansion
T temperature of the fluid
C species concentration in the fluid
υ kinematic viscosity
k thermal conductivity of the fluid
T_w temperature of the plate at $y = 0$
C_w species concentration at the plate, at $y = 0$
ρ density
Ha Hartmann number
m Hall current parameter
R Radiation parameter,
Sc Schmidt number
$\bar{u}, \bar{v}$ dimensionless velocity in x & z direction
Gm mass Grashof number
$\bar{C}$ dimensionless concentration
g acceleration due to gravity
μ the coefficient of viscosity
β^* volumetric coefficient of concentration expansion
T_∞ temperature of the plate at $y \to \infty$
C_∞ species concentration at $y \to \infty$
C_P specific heat at constant pressure
D mass diffusion coefficient
B_0 uniform magnetic field
σ electrical conductivity
Gr thermal Grashof number
α angle of inclination of magnetic field from horizontal
u,v velocities of the fluid in x & z-directions
$\bar{t}$ dimensionless time
Pr Prandtl number
θ dimensionless temperature
σ^* Stefan Boltzmann constant
Ω - angular velocity