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The effect of chemical reaction and thermal radiation on the hydro magnetic free convective rotating flow past an accelerated vertical plate in the presence variable heat and mass diffusion

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ABSTRACT

The effects of chemical reaction and thermal radiation on MHD flow of an incompressible fluid past an accelerated plate with variable heat and mass transfer through porous medium in the presence of rotation have been considered. The plate temperature and concentration level are raised linearly with time. The Laplace transform method is used to solve the governing equations. The results are discussed in detail with the help of graphs and tables to observe the effects of various parameters.

Keywords: Chemical reaction, Thermal radiation, rotation, porous medium, skin friction, Nusselt number, Sherwood number.

INTRODUCTION

Importance of MHD flows in which the heat and mass transfer occur simultaneously in a porous medium has attracted the attention of many scientists and research scholars due to its possible application in diverse fields of science and technology such as soil sciences, astrophysics, nuclear reactors etc. Kim [7] studied the magneto hydrodynamic convective heat transfer past a semi infinite vertical porous moving plate with variable suction. Hossain and Mandal [4] discussed the mass transfer effects on the unsteady hydro magnetic free convection flow past an accelerated vertical porous plate. Jha [5] investigated the hydro magnetic free convection flow through a porous medium with mass transfer.

The study of chemical reaction effects on heat and mass transfer flow is very useful for improving a number of chemical technologies such as food processing, polymer production, manufacturing of ceramics etc. Chambre and Young [1] analyzed the effects of homogeneous first order chemical reactions in the neighbourhood of a flat plate for destructive and generative reactions. Senapati et.al [13] have studied the effects of chemical reaction on mass and heat transfer on MHD free convection flow of fluids in vertical plates and in between parallel plates for slips flow regions. Mass transfer effects on a moving isothermal vertical plate in the presence of chemical reaction were studied by Das et.al [6]. In many industrial and environmental processes radiative convective flows with heat and mass transfer are playing vital role. The effects of thermal radiation and mass diffusion occur if the temperature of surrounding fluid is rather high. Some of the engineering applications of this phenomenon are gas turbines, satellites and space vehicles etc. Cogley et.al [2] studied radiative heat transfer in a non-gray gas near equilibrium. Cookey and Sigalo [10] investigated unsteady MHD free convection flow with radiative heat transfer.

The rotating flow of electrically conducting fluid in presence of a magnetic field is encountered in Geophysical fluid dynamics. It is well known that a number of astronomical bodies possess fluid interiors and magnetic fields. Changes that take place in the rate of rotation suggest the possible importance of hydro magnetic spin up. Jana et.al [3], Singh et.al [12], Singh K.D [8], Singh et.al [11], Senapati et.al [14] have investigated these problems of spin up in MHD under different conditions. Recently Muthucumaraswamy et.al [15] presented the MHD flow past an accelerated vertical plate with variable heat and mass diffusion in the presence of rotation. Here the effects of radiation and chemical reaction were not considered.

Hence it is proposed to study the MHD flow past an accelerated vertical plate with heat and mass transfer in a rotating system under the effects of radiation and chemical reaction in a porous medium due to its numerous applications mentioned above.

Mathematical Formulation:
The unsteady hydro magnetic flow of an electrically conducting fluid induced by viscous incompressible fluid past a uniformly accelerated motion of an infinite vertical plate is considered. Here the fluid and the plate rotate as a rigid body with a uniform angular velocity Ω about y^*-axis in the presence of an imposed uniform magnetic field B_0 normal to the plate. Initially the temperature and concentration of the system are assumed to be T_∞^* and C_∞^*. At time $t^* > 0$, the plate starts moving with a velocity $u = u_0 t^*$ in its own plane and the temperature of the plate as well as wall concentration near the plate are raised linearly with time. Since the plate occupying the plane $y^* = 0$ is of infinite extent, all the physical quantities depend only on y^* and t^*. After neglecting the induced magnetic field and under the usual Boussinesq's approximation, the flow of electrically conducting fluid in a rotating system can be shown to be governed by the following system of equations

$$\frac{\partial u^*}{\partial t^*} - 2\Omega w^* = g\beta(T^* - T_\infty^*) + g\beta_c(C^* - C_\infty^*) + \nu\frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\sigma {B_0}^2 u^*}{\rho} - \frac{\nu u^*}{K^*} \tag{1}$$

$$\frac{\partial w^*}{\partial t^*} + 2\Omega u^* = \nu\frac{\partial^2 w^*}{\partial y^{*2}} - \frac{\sigma {B_0}^2 w^*}{\rho} - \frac{\nu\, w^*}{K^*} \tag{2}$$

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

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - R_c(C^* - C_\infty^*) \tag{4}$$

The initial and boundary conditions are as follows:

$$w^* = 0, u^* = 0, T^* = T_\infty^*, C^* = C_\infty^* \quad \text{for all } y^*, t^* \le 0$$

For $t^* > 0$,

$$\left.\begin{array}{l} u^* = u_0 t^*, C^* = C_\infty^* + (C_w^* - C_\infty^*)At^* \\ w^* = 0, T^* = T_\infty^* + (T_w^* - T_\infty^*)At^* \end{array}\right\} \quad \text{at } y = 0 \tag{5}$$

$$u^* \to 0, T^* \to T_\infty^*, C^* \to C_\infty^* \qquad \text{at } y \to \infty$$

The radiative heat flux term is simplified by making use of the Rosseland approximation [9]

as $$q_r = \frac{-4}{3}\frac{\sigma^*}{a^*}\frac{\partial T^{*4}}{\partial y^*} \tag{6}$$

where σ^* and $a^*$are the Stefan-Boltzmann constant and the mean absorption coefficient respectively. It should be noted that by using the Rosseland approximation, we limit our analysis to optically thik fluids. If temperature differences within the flow are sufficiently small, such that ${T^*}^4$may be expressed as a linear function of the temperature, then the Taylor series for ${T^*}^4$ about T_∞^* , after neglecting higher order terms, is given by

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

Substituting (6) and (7) in (3) we have

$$\rho C_p \frac{\partial T^*}{\partial t^*} = \left[k + \frac{16}{3}\frac{\sigma^*}{a^*}{T_\infty^*}^3\right]\frac{\partial^2 T^*}{\partial y^{*2}} \tag{8}$$

Taking the following non dimensional quantities

$$u = \frac{u^*}{(\nu u_0)^{\frac{1}{3}}}, w = \frac{w^*}{(\nu u_0)^{\frac{1}{3}}}, t = t^*\left(\frac{{u_0}^2}{\nu}\right)^{\frac{1}{3}}, y = y^*\left(\frac{u_0}{\nu^2}\right)^{\frac{1}{3}}, \theta = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*},$$

$$Gr = \frac{g\beta(T_w^* - T_\infty^*)}{u_0}, Gm = \frac{g\beta_c(C_w^* - C_\infty^*)}{u_0}, C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*}, M = \frac{\sigma {B_0}^2}{\rho}\left(\frac{\nu}{{u_0}^2}\right)^{\frac{1}{3}},$$

$$Pr = \frac{\mu C_p}{k}, Sc = \frac{\nu}{D}, A = \left(\frac{{u_0}^2}{\nu}\right)^{\frac{1}{3}}, K = K^*\left(\frac{u_0}{\nu^2}\right)^{\frac{2}{3}}, E = \frac{\Omega \nu^{\frac{1}{3}}}{u_0^{\frac{2}{3}}}, R = \frac{16}{3}\frac{\sigma {T_\infty^*}^3}{a^* k}, R_c = \frac{{R_c}^* \nu^{\frac{1}{3}}}{u_0^{\frac{2}{3}}}$$

equations (1), (2), (8) and (4) reduce to

$$\frac{\partial u}{\partial t} - 2Ew = \frac{\partial^2 u}{\partial y^2} + Gr\theta + GmC - Mu - \frac{u}{K} \quad (9)$$

$$\frac{\partial w}{\partial t} + 2Eu = \frac{\partial^2 w}{\partial y^2} - Mw - \frac{w}{K} \quad (10)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2}(1 + R) \quad (11)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - R_c C \quad (12)$$

From equations (9) and (10), we get

$$\frac{\partial p}{\partial t} = \frac{\partial^2 p}{\partial y^2} + Gr\theta + GmC - \alpha p \quad (13)$$

where $p = u + iw$, $\alpha = M + \frac{1}{K} + 2Ei$

From (5) the transformed initial and boundary conditions are

$p = 0, \theta = 0, C = 0$ for all $y, t \leq 0$

for t > 0,

$$p = t, \theta = t, C = t \quad \text{at} \quad y = 0 \quad (14)$$

$p \to 0, C \to 0, \theta \to 0$ as $y \to \infty$

Method of Solution

The equations (11) to (13) are nonlinear, coupled partial differential equations. So we want to solve them by using Laplace transform technique. Taking Laplace Transform, the equations (11), (12) and (13) reduce to

$$\frac{\partial^2 \bar{\theta}}{\partial y^2} - \frac{Pr}{1+R}s\bar{\theta} = 0 \quad (15)$$

$$\frac{\partial^2 \bar{C}}{\partial y^2} - Sc(s + Rc)\bar{C} = 0 \quad (16)$$

$$\frac{\partial^2 \bar{p}}{\partial y^2} - (s + \alpha)\bar{p} = -Gr\bar{\theta} - Gm\bar{C} \quad (17)$$

where'‘s’ is Laplace transform parameter.

The boundary conditions given by (14) reduce to

$\bar{p} = 0, \bar{\theta} = 0, \bar{C} = 0,$ for all $y, t \leq 0$

For t > 0 :

$$\bar{p} = \frac{1}{s^2}, \bar{\theta} = \frac{1}{s^2}, \bar{C} = \frac{1}{s^2} \quad \text{at} \quad y = 0$$

$$\bar{p} \to 0, \bar{\theta} \to 0, \bar{C} \to 0 \quad \text{as} \quad y \to \infty \quad (18)$$

Solving (15), (16) and (17) with the boundary conditions (18) we get

$$\bar{\theta} = \frac{1}{s^2} e^{-\sqrt{a_1 s} y} \tag{19}$$

$$\bar{C} = \frac{1}{s^2} e^{-\sqrt{Sc(s+Rc)} y} \tag{20}$$

$$\bar{p} = \left\{\frac{1}{s^2} + \frac{Gr}{s^2((a_1-1)s-\alpha)} + \frac{Gm}{s^2((Sc-1)s+ScRc-\alpha)}\right\} e^{-y\sqrt{s+\alpha}} - \frac{Gr}{s^2((a_1-1)s-\alpha)} e^{-y\sqrt{a_1 s}} - \frac{Gm}{s^2((Sc-1)s+ScRc-\alpha)} e^{-y\sqrt{Sc(s+Rc)}} \tag{21}$$

Inverting the equations (19), (20) and (21), we get

$$\theta = t erfc(\eta\sqrt{a_1}) - 2\eta t\sqrt{\frac{a_1}{\pi}} e^{-\eta^2 a_1} + 2\eta^2 t a_1 erfc(\eta\sqrt{a_1}) \tag{22}$$

$$C = \left(\frac{t}{2} + \frac{\eta}{2}\sqrt{\frac{tSc}{Rc}}\right) e^{2\eta\sqrt{tScRc}} erfc\left(\eta\sqrt{Sc} + \sqrt{tRc}\right) + \left(\frac{t}{2} - \frac{\eta}{2}\sqrt{\frac{tSc}{Rc}}\right) e^{-2\eta\sqrt{tScRc}} erfc\left(\eta\sqrt{Sc} - \sqrt{tRc}\right) \tag{23}$$

Case-1: $Sc \neq 1$

$$p = e^{-2\eta\sqrt{\alpha t}} erfc\left(\eta - \sqrt{\alpha t}\right)\left(\frac{t}{2} - \eta\sqrt{t} - \frac{Gra_2}{2\alpha^2} - \frac{t}{2\alpha} + \frac{\eta\sqrt{t}}{\alpha} - \frac{Gma_3}{2a_4^2} + \frac{t}{2a_4} - \frac{\eta\sqrt{t}}{a_4}\right)\eta + e^{2\eta\sqrt{\alpha t}} erfc\left(\eta + \sqrt{\alpha t}\right)\left(\frac{t}{2} + \eta\sqrt{t} - \frac{Gra_2}{2\alpha^2} - \frac{t}{2\alpha} - \frac{\eta\sqrt{t}}{\alpha} - \frac{Gma_3}{2a_4^2} + \frac{t}{2a_4} + \frac{\eta\sqrt{t}}{a_4}\right)$$
$$+ \frac{Gra_2}{2\alpha^2} e^{\frac{\alpha t}{a_2}}\left(e^{-2\eta\sqrt{\left(\frac{\alpha}{a_2}+\alpha\right)t}} erfc\left(\eta - \sqrt{\left(\frac{\alpha}{a_2}+\alpha\right)t}\right) + e^{2\eta\sqrt{\left(\frac{\alpha}{a_2}+\alpha\right)t}} erfc\left(\eta + \sqrt{\left(\frac{\alpha}{a_2}+\alpha\right)t}\right)\right)$$
$$+ \frac{Gma_3}{2a_4^2} e^{\frac{-a_4 t}{a_3}}\left(e^{-2\eta\sqrt{\left(\frac{-a_4}{a_3}+\alpha\right)t}} erfc\left(\eta - \sqrt{\left(\frac{-a_4}{a_3}+\alpha\right)t}\right) + e^{2\eta\sqrt{\left(\frac{-a_4}{a_3}+\alpha\right)t}} erfc\left(\eta + \sqrt{\left(\frac{-a_4}{a_3}+\alpha\right)t}\right)\right) -$$
$$Gr\left[\frac{-a_2}{\alpha^2} erfc(\eta\sqrt{a_1}) - \frac{1}{\alpha}\left(t erfc(\eta\sqrt{a_1}) - 2\eta t\sqrt{\frac{a_1}{\pi}} e^{-a_1\eta^2} + 2\eta^2 t a_1 erfc(\eta\sqrt{a_1})\right) + \right.$$
$$\left.\frac{a_2}{2\alpha^2} e^{\frac{\alpha t}{a_2}}\left(e^{-2\eta\sqrt{\frac{ta_1\alpha}{a_2}}} erfc\left(\eta\sqrt{a_1} - \sqrt{\frac{\alpha t}{a_2}}\right) + e^{2\eta\sqrt{\frac{ta_1\alpha}{a_2}}} erfc\left(\eta\sqrt{a_1} + \sqrt{\frac{\alpha t}{a_2}}\right)\right)\right] - Gm\left[\frac{-a_3}{2a_4^2}\left(e^{-2\eta\sqrt{tScRc}} erfc\left(\eta\sqrt{Sc} - \sqrt{tRc}\right) + e^{2\eta\sqrt{tScRc}} erfc\left(\eta\sqrt{Sc} + \sqrt{tRc}\right)\right) + \right.$$
$$\frac{1}{a_4}\left(\left(\frac{t}{2} + \frac{\eta}{2}\sqrt{\frac{tSc}{Rc}}\right) e^{2\eta\sqrt{tScRc}} erfc\left(\eta\sqrt{Sc} + \sqrt{tRc}\right) + \left(\frac{t}{2} - \frac{\eta}{2}\sqrt{\frac{tSc}{Rc}}\right) e^{2\eta\sqrt{tScRc}} erfc\left(\eta\sqrt{Sc} - \sqrt{tRc}\right)\right) +$$
$$\left.\frac{a_3}{2a_4} e^{\frac{-a_4 t}{a_3}}\left(e^{-2\eta\sqrt{tSc\left(\frac{-a_4}{a_3}+Rc\right)}} erfc\left(\eta\sqrt{Sc} - \sqrt{t\left(\frac{-a_4}{a_3}+Rc\right)}\right) + e^{2\eta\sqrt{tSc\left(\frac{-a_4}{a_3}+Rc\right)}} erfc\left(\eta\sqrt{Sc} + \sqrt{t\left(\frac{-a_4}{a_3}+Rc\right)}\right)\right)\right] \tag{24}$$

Case-2: Sc =1

$$p =$$
$$\left(1 + \frac{Gm}{Rc-\alpha}\right)\left[\left(\frac{t}{2} - \eta\sqrt{t}\right) e^{-2\eta\sqrt{\alpha t}} erfc\left(\eta - \sqrt{\alpha t}\right) + \left(\frac{t}{2} + \eta\sqrt{t}\right) e^{2\eta\sqrt{\alpha t}} erfc\left(\eta + \sqrt{\alpha t}\right)\right] + Gr\left[\frac{-a_2}{2\alpha^2}\left(e^{-2\eta\sqrt{\alpha t}} erfc\left(\eta - \sqrt{\alpha t}\right) + e^{2\eta\sqrt{\alpha t}} erfc\left(\eta + \sqrt{\alpha t}\right)\right) - \frac{1}{\alpha}\left(\left(\frac{t}{2} - \eta\sqrt{t}\right) e^{-2\eta\sqrt{\alpha t}} erfc\left(\eta - \sqrt{\alpha t}\right) + \left(\frac{t}{2} + \eta\sqrt{t}\right) e^{2\eta\sqrt{\alpha t}} erfc\left(\eta + \sqrt{\alpha t}\right)\right) + \right.$$
$$\left.\frac{a_2}{2\alpha^2} e^{\frac{\alpha t}{a_2}}\left(e^{-2\eta\sqrt{t\left(\frac{\alpha}{a_2}+\alpha\right)}} erfc\left(\eta - \sqrt{t\left(\frac{\alpha}{a_2}+\alpha\right)}\right) + e^{2\eta\sqrt{t\left(\frac{\alpha}{a_2}+\alpha\right)}} erfc\left(\eta + \sqrt{t\left(\frac{\alpha}{a_2}+\alpha\right)}\right)\right)\right]$$
$$- \frac{Gm}{Rc-\alpha}\left[\left(\frac{t}{2} - \eta\sqrt{t}\right) e^{-2\eta\sqrt{Rct}} erfc\left(\eta - \sqrt{Rct}\right) + \left(\frac{t}{2} + \eta\sqrt{t}\right) e^{2\eta\sqrt{Rct}} erfc\left(\eta + \sqrt{Rct}\right)\right]$$

$$-Gr\left[\frac{-a_2}{\alpha^2}erfc(\eta\sqrt{a_1})-\frac{1}{\alpha}\left(terfc(\eta\sqrt{a_1})-2\eta t\sqrt{\frac{a_1}{\pi}}e^{-\eta^2 a_1}+2\eta^2 ta_1 erf(\eta\sqrt{a_1})\right)+\right.$$
$$\left.\frac{a_2}{2\alpha^2}e^{\frac{\alpha t}{a_2}}\left(e^{-2\eta\sqrt{\frac{ta_1\alpha}{a_2}}}erfc\left(\eta\sqrt{a_1}-\sqrt{\frac{\alpha t}{a_2}}\right)+e^{2\eta\sqrt{\frac{ta_1\alpha}{a_2}}}erfc\left(\eta\sqrt{a_1}+\sqrt{\frac{\alpha t}{a_2}}\right)\right)\right] \quad (25)$$

$$\alpha=M+\frac{1}{K}+2iE, a_1=\frac{Pr}{1+R}, a_2=a_1-1, a_3=Sc-1, a_4=ScRc-\alpha, \eta=\frac{y}{2\sqrt{t}}$$

Skin friction at the surface of the plate is given by

$$\tau=-\left[\frac{\partial p}{\partial y}\right]_{y=0}=-\frac{1}{2\sqrt{t}}\left[\frac{\partial p}{\partial \eta}\right]_{\eta=0}$$
$$=-\frac{1}{2\sqrt{t}}\left[\left(\frac{t}{2}-\frac{Gra_2}{2\alpha^2}-\frac{Gma_3}{2{a_4}^2}+\frac{t}{a_4}\right)\left(-\frac{4}{\sqrt{\pi}}e^{-\alpha t}-4\sqrt{\alpha t}erf(\sqrt{\alpha t})\right)-2\left(\sqrt{t}-\frac{\sqrt{t}}{\alpha}+\frac{\sqrt{t}}{a_4}\right)erf(\sqrt{\alpha t})+\right.$$
$$\frac{Gra_2}{2\alpha^2}e^{\frac{\alpha t}{a_2}}\left(-4\sqrt{t\left(\frac{\alpha}{a_2}+\alpha\right)}erf\left(\sqrt{t\left(\frac{\alpha}{a_2}+\alpha\right)}\right)-\frac{4}{\sqrt{\pi}}e^{-\left(\frac{\alpha}{a_2}+\alpha\right)t}\right)+$$
$$\frac{Gma_3}{2{a_4}^2}e^{\frac{-a_4 t}{a_3}}\left(-4\sqrt{t\left(\frac{-a_4}{a_3}+\alpha\right)}erf\left(\sqrt{t\left(\frac{-a_4}{a_3}+\alpha\right)}\right)-\frac{4}{\sqrt{\pi}}e^{-\left(\frac{-a_4}{a_3}+\alpha\right)t}\right)-$$
$$Gr\left(\frac{2\sqrt{a_1}}{\sqrt{\pi}}\left(\frac{a_2}{\alpha^2}+\frac{2t}{\alpha}\right)+\frac{a_2}{2\alpha^2}e^{\frac{\alpha t}{a_2}}\left(-4\sqrt{\frac{\alpha a_1 t}{a_2}}erf\left(\sqrt{\frac{\alpha t}{a_2}}\right)-4\frac{\sqrt{a_1}}{\sqrt{\pi}}e^{-\frac{\alpha t}{a_2}}\right)\right)-Gm\left(\frac{-a_3}{2a_4^2}\left(-4\sqrt{ScRct}erf(\sqrt{tRc})-\right.\right.$$
$$\left.\frac{4\sqrt{Sc}}{\sqrt{\pi}}e^{-tRc}\right)+\frac{1}{a_4}\left(-2t\sqrt{ScRct}erf(\sqrt{tRc})-\frac{2t\sqrt{Sc}}{\sqrt{\pi}}e^{-tRc}-\sqrt{\frac{tSc}{Rc}}erf(\sqrt{tRc})\right)+$$
$$\left.\left.\frac{a_3}{2a_4^2}e^{\frac{-a_4 t}{a_3}}\left(-4\sqrt{tSc\left(\frac{-a_4}{a_3}+Rc\right)}erf\left(\sqrt{t\left(\frac{-a_4}{a_3}+Rc\right)}\right)-\frac{4\sqrt{Sc}}{\sqrt{\pi}}e^{-\left(\frac{-a_4}{a_3}-\right)t}\right)\right)\right] \quad (26)$$

The Nusselt number and the Sherwood number at the plate are respectively

$$Nu=-\left(\frac{\partial\theta}{\partial y}\right)_{y=0}=-\frac{1}{2\sqrt{t}}\left[\frac{\partial\theta}{\partial\eta}\right]_{\eta=0}=2\sqrt{\frac{ta_1}{\pi}} \quad (27)$$

$$Sh=-\left(\frac{\partial C}{\partial y}\right)_{y=0}=-\frac{1}{2\sqrt{t}}\left[\frac{\partial C}{\partial\eta}\right]_{\eta=0}=\sqrt{\frac{tSc}{\pi}e^{-tRc}}+\frac{\sqrt{Sc}}{2}\left(2t\sqrt{Rc}+\frac{1}{\sqrt{Rc}}\right)erf(\sqrt{Rct}) \quad (28)$$

RESULTS AND DISCUSSION

Thermal radiation and chemical reaction effects on MHD flow past an accelerated vertical plate in a porous medium with variable heat and mass transfer in the presence of rotation have been studied. The governing equations are solved by Laplace transform method. The effects of various parameters entering in the governing equations on the velocity, temperature, concentration, skin friction, Nusselt number, and Sherwood number are shown through graphs and tables.

Fig.1 depicts the effects of magnetic field parameter, Grashof number (Gr), and modified Grashof number (Gm) on the primary velocity. It is noted that upon increasing the values of Gm and Gr, increase the velocity. On the other hand velocity decreases when M increase.

In **Fig.2** Primary velocity profiles for different values of Prandtl number (Pr), Rotation parameter (E), and thermal radiation parameter (R) are plotted. It is observed that velocity decreases when Pr and E increase. But Radiation parameter accelerates the flow when it increases.

Fig.3 shows the effects of Schmidt number (Sc), Permeability parameter (K) and chemical reaction parameter (Rc). It is observed that the increasing values of K increase the primary velocity. But other two parameters show opposite effect.

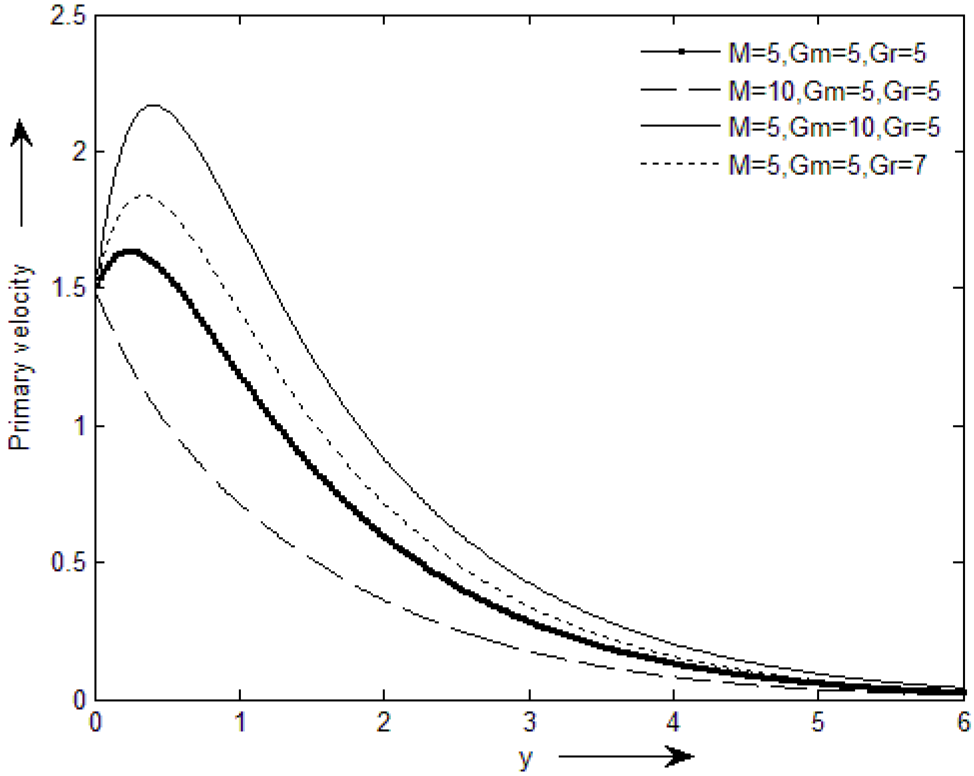

Fig.1.primary velocity profiles for various values of M, Gm, and Gr when Pr=0.71, E=1, R=1, Sc=0.16, Rc=2, t=1.5, K=2

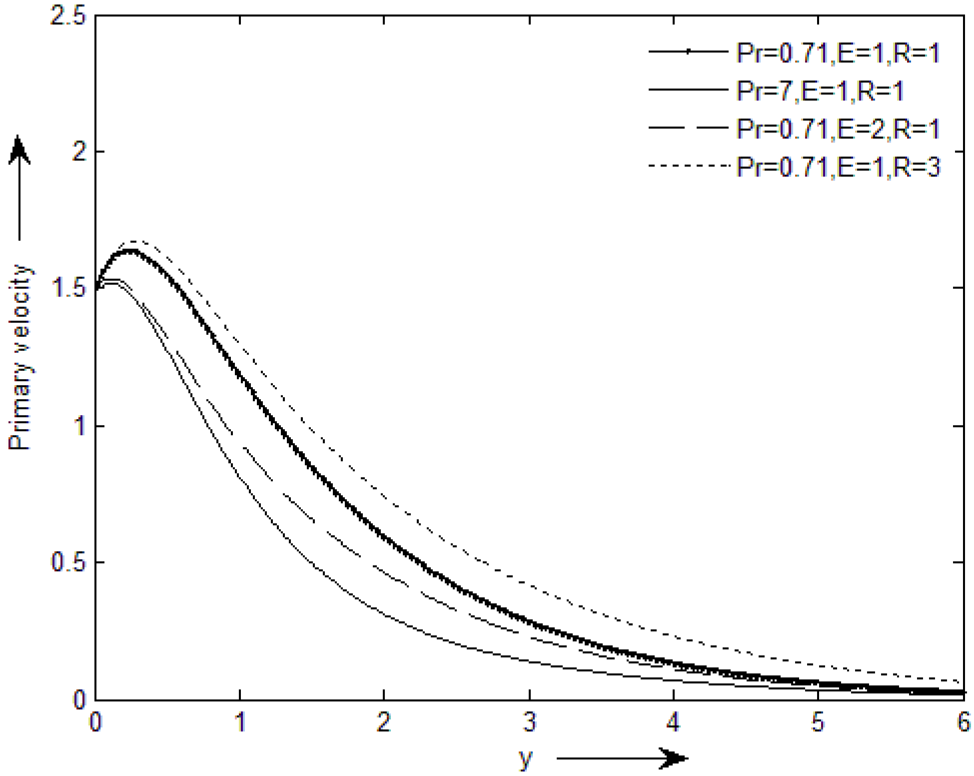

Fig.2.primary velocity profiles for various values of Pr, E, and R when Gm=5, Gr=5, M=5, Sc=0.16, Rc=2, t=1.5, K=2

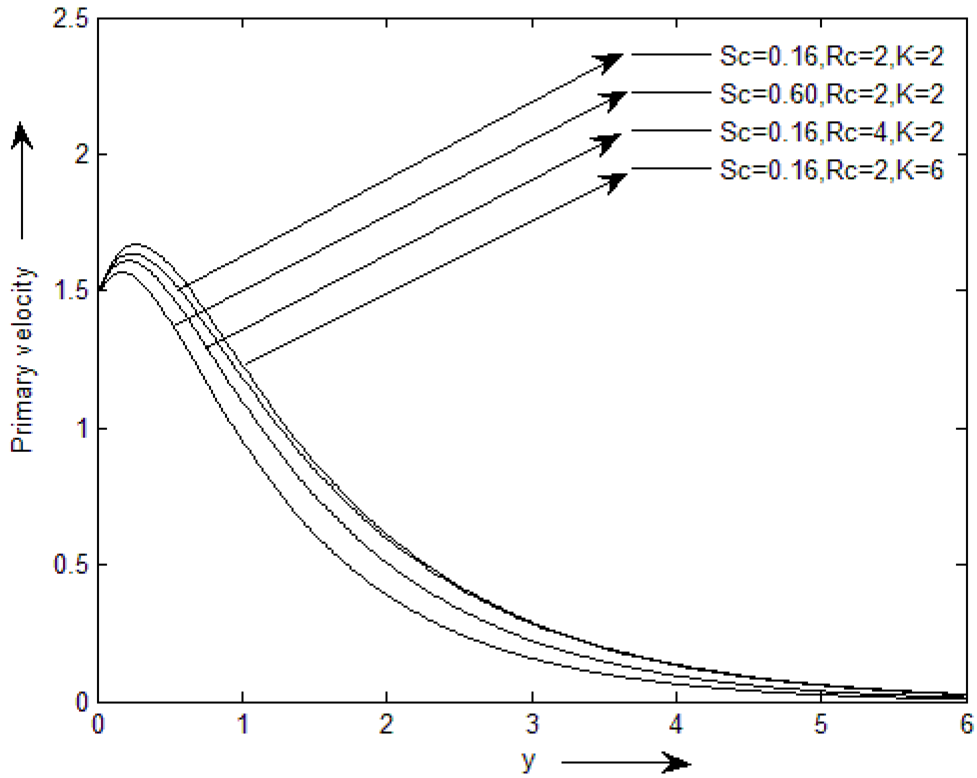

Fig.3.primary velocity profiles for various values of Sc, Rc, and K when Pr=0.71, E=1, R=1, Gm=5, Gr=5, t=1.5, M=5

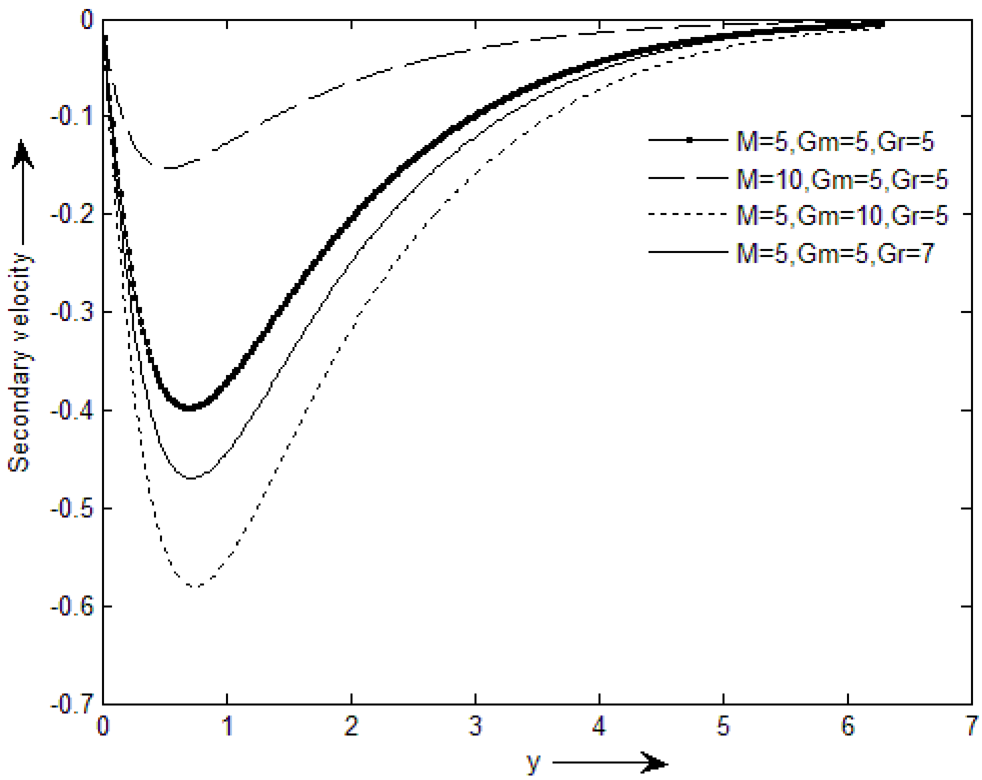

Fig.4.Secondary velocity profiles for various values of M, Gm, and Gr when Pr=0.71, E=1, R=1, Sc=0.16, Rc=2, t=1.5, K=2

Fig.4 illustrates the variations of secondary velocity with various values of M, Gm, and Gr. Here it is noted that the effects of all the three parameters are reverse of that they show for primary velocity.

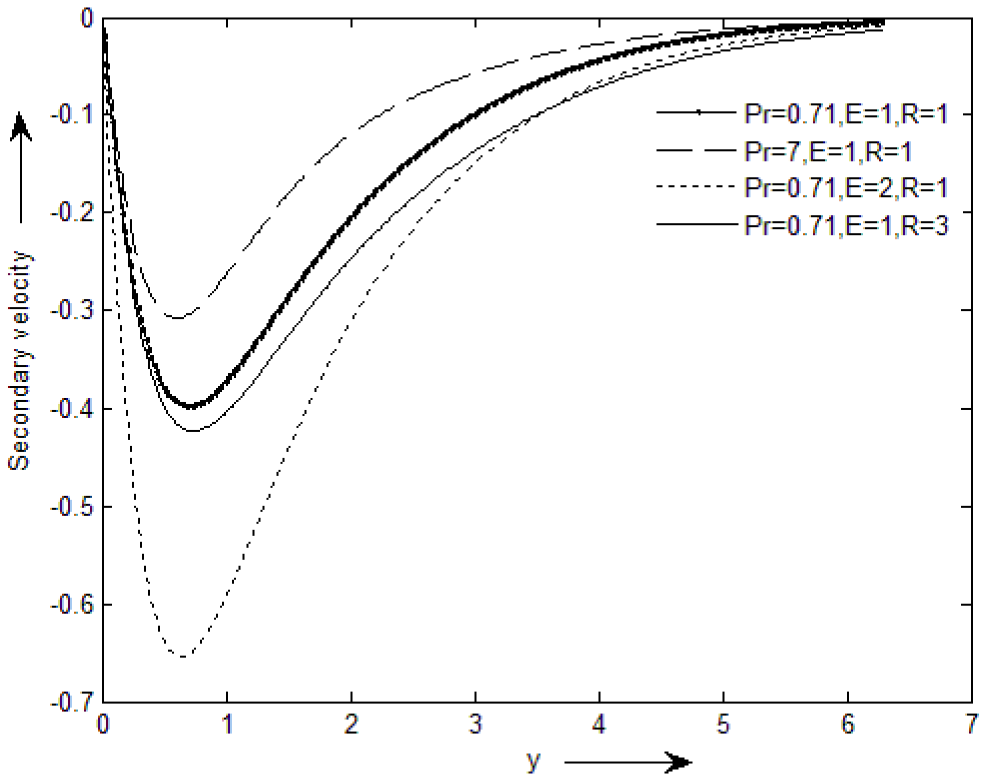

Fig.5.Secondary velocity profiles for various values of Pr, E, and R when Gm=5, Gr=5, M=5, Sc=0.16, Rc=2, t=1.5, K=2

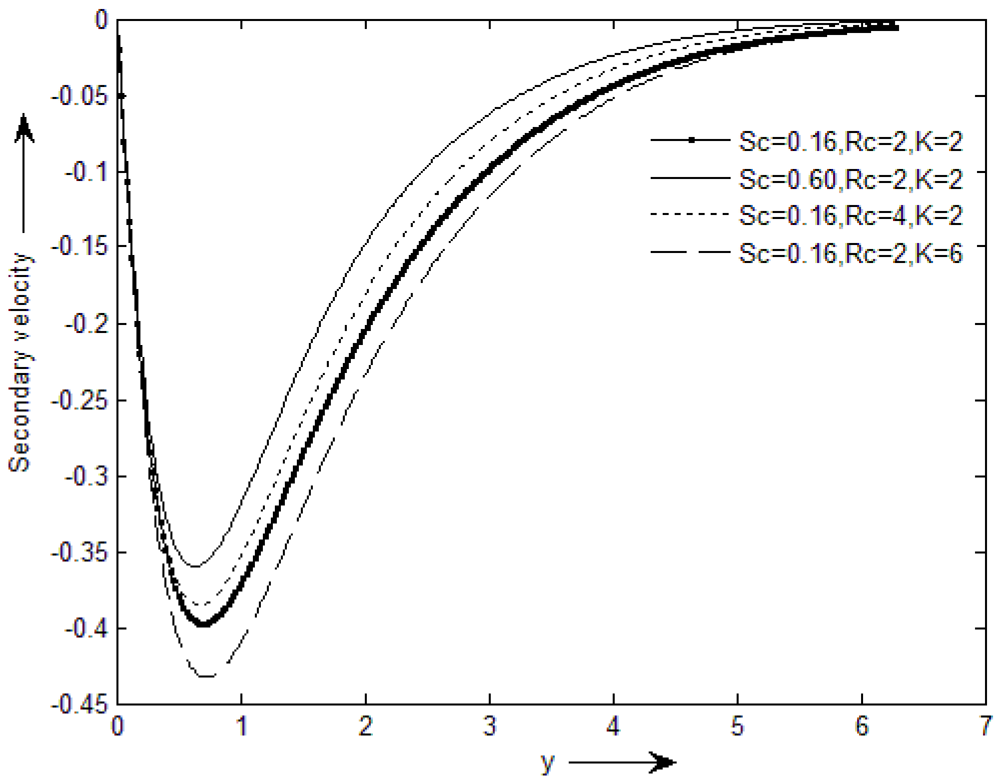

Fig.6.Secondary velocity profiles for various values of Sc, Rc and K when Pr=0.71, E=1, R=1, Gm=5, Gr=5, t=1.5, M=5

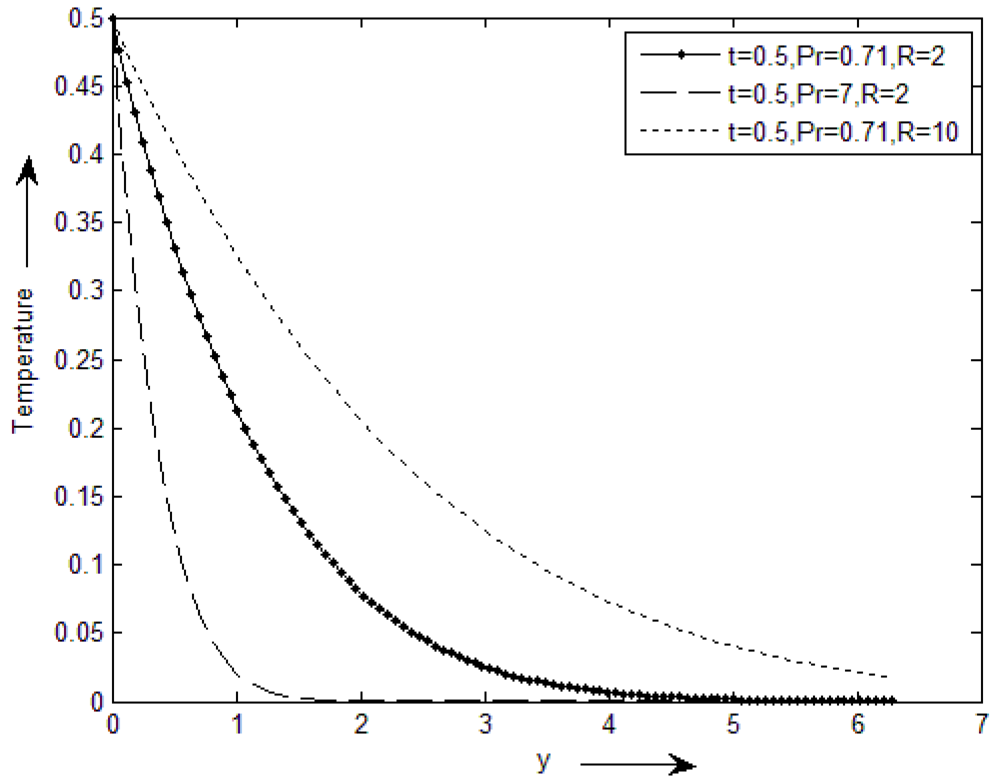

Fig.7. Temperature profiles for various values of Pr and R

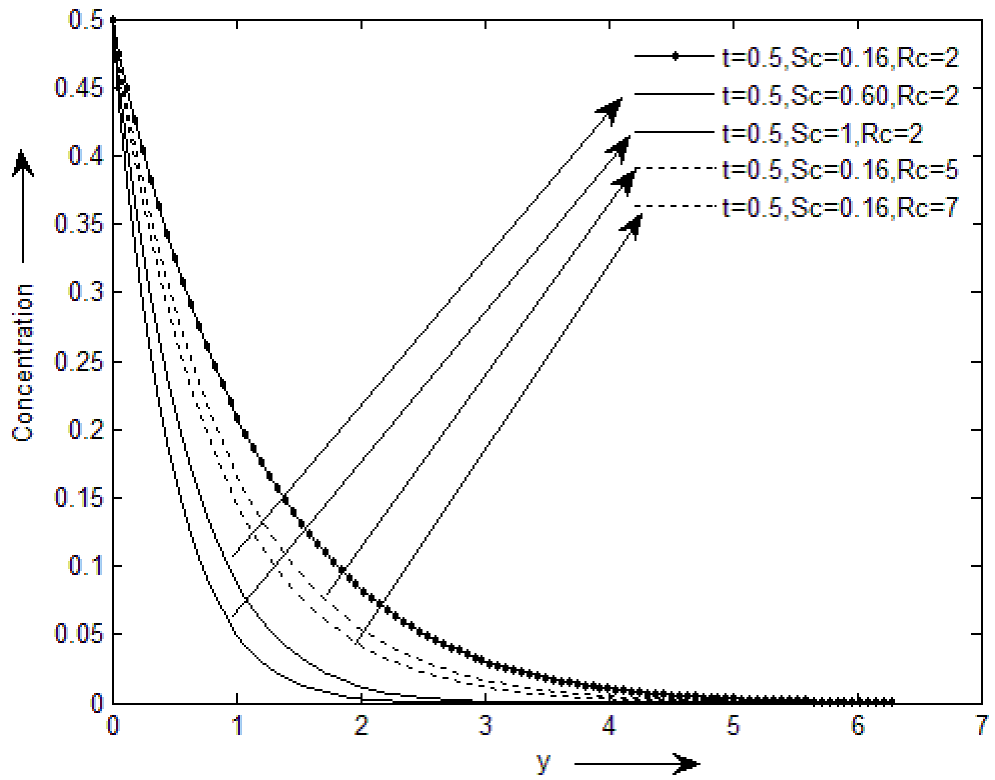

Fig.8. Concentration profiles for various values of Sc and Rc

Fig.5 reveals the effects of Pr, E, and R on secondary velocity. It is observed that velocity increases as Pr increase. But the parameters E and R have opposite effects.

In **Fig.6,** it is noted that increasing values of Sc and Rc result an increase in secondary velocity. Again velocity decreases as parameter K increase.

Fig.7 presents the temperature profiles for various values of Pr and R. It is observed that the fluid temperature falls monotonically when the Prandtl number is increased. On the other hand increasing values of R helps to rise in temperature.

The concentration profiles for various values of Schmidt number (Sc) and chemical reaction parameter (Rc) are drawn in **Fig.8**. It is evident from the figure that concentration decreases with increase in Sc and Rc.

Table.1 presents the numerical values of skin friction (τ) at the plate due to variations in Gr, Gm, M, Pr, R, Rc, Sc, E, K at t=1.5. It is noted that skin friction decreases as R and K increase. The other parameters show opposite effects on skin friction.

Nusselt number and Sherwood number are evaluated numerically in **Table.2** and **Table.3** respectively. It is observed that when Pr increases Nusselt number increases. But increasing values of R decrease it. On the other hand Sherwood number increases as Sc and Rc increase.

Table.1: Numerical values of skin friction at t=1.5

Sr.No	Gr	Gm	M	Pr	R	Rc	Sc	E	K	τ
1	2	2	1	0.71	1	2	0.60	1	1	9.835
2	4	2	1	0.71	1	2	0.60	1	1	11.534
3	2	4	1	0.71	1	2	0.60	1	1	14.024
4	2	2	2	0.71	1	2	0.60	1	1	43.536
5	2	2	1	7	1	2	0.60	1	1	411.409
6	2	2	1	0.71	4	2	0.60	1	1	8.002
7	2	2	1	0.71	1	4	0.60	1	1	10.184
8	2	2	1	0.71	1	2	1.5	1	1	16.276
9	2	2	1	0.71	1	2	0.60	3	1	33.876
10	2	2	1	0.71	1	2	0.60	1	3	6.863

Table.2: Numerical values of Nusselt number

Sr. No	t	Pr	R	Nu
1	1.5	0.71	2	0.672
2	0.5	0.71	2	0.388
3	1.5	7	2	2.111
4	1.5	0.71	4	0.520

Table.3: Numerical values of Sherwood number

Sr. No	t	Sc	Rc	Sh
1	1.5	0.60	2	1.9163
2	0.5	0.60	2	0.8060
3	1.5	1.5	2	3.0299
4	1.5	0.60	4	2.5174

Conclusion:

1. Increasing values of the parameters Gm, Gr and K help to increase the primary velocity.
2. The parameters M, Rc, Sc, Pr and E have same effect on primary velocity. When these parameters increase, primary velocity decreases.
3. Increasing values of Pr, M, Sc and Rc result an increase in secondary velocity.
4. On the other hand secondary velocity decreases when the parameters Gm, Gr, E, R, and K increase.
5. Increasing values of R help to raise the temperature. But Pr has opposite effect on it.
6. Concentration decreases when both the parameters Sc and Rc increase.
7. Except R and K, Increasing values of all the parameters help to increase the skin friction.

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