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## MHD flow of Rotating fluid past an Infinite Vertical Porous plate with Heat and mass transfer

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### Abstract

In this paper, we have discussed the unsteady hydromagnetic natural convective rotating flow of an electrically conducting, viscous, incompressible and optically thick radiating second grade fluid past an impulsively moving vertical plate entrenched in a fluid inundated porous medium, while temperature of the plate has a temporarily ramped profile. The solutions of the governing equations are obtained by making use of Laplace transform technique. The expressions for skin friction due to primary and secondary flows and Nusselt number are derived for both ramped temperature and isothermal plates. Sherwood number is also obtained. The velocity, temperature and concentration are exhibited graphically whereas the skin friction components, Nusselt number and Sherwood number are in tabular form with reference to governing parameters.

*Key words:* MHD flows, porous medium, convection flows, vertical plate, ramped temperature, isothermal plate

**AMS Subject classification codes:** 80A20, 76W05, 76E06, 76D50

### Nomenclature

$u, w$	Fluid velocity in $x$ and $z$ -direction
$g$	Acceleration due to gravity
$k^*$	Rossland mean absorption coefficient
$C_p$	specific heat at constant pressure

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$k$	Thermal conductivity of the fluid
$K_1$	Permeability of the porous medium
$q_r$	radiative flux vector
$D$	chemical molecular diffusivity
$q$	the velocity vector,
$H$	the magnetic field intensity vector,
$E$	the electric field ,
$J$	the current density vector,
$\omega_e$	the cyclotron frequency
$U_0$	uniform velocity of the plate
$M^2$	Hartmann number,
$R$	Rotation parameter,
$K$	Permeability parameter,
$Gr$	thermal Grashof number,
$Gc$	mass Grashof number,
$Pr$	Prandtl number
$N$	thermal radiation parameter and
$Sc$	the Schmidt number
$H(t-1)$	unit step function
$erfc(x)$	complementary error function
$\beta$	volumetric coefficient of thermal expansion
$\beta^*$	volumetric coefficient of expansion for species concentration
$\mu_e$	the magnetic permeability
$\Omega$	Uniform angular velocity
$\sigma^*$	Stefan–Boltzmann constant.
$\nu$	Coefficient of kinematic viscosity
$\rho$	fluid density
$\sigma$	electrical conductivity
$\theta$	fluid temperature
$\phi$	species concentration

## 1. Introduction

The study of free convection flow induced by the simultaneous action of thermal and solutal buoyancy forces acting over bodies with different geometries in a fluid with porous medium is prevalent in many natural

phenomena and has varied a wide range of industrial applications. For example, the presence of pure air or water is impossible because some foreign mass may be present either naturally or mixed with air or water due to industrial emissions, in atmospheric flows. Natural processes such as attenuation of toxic waste in water bodies, vaporization of mist and fog, photosynthesis, transpiration, sea-wind formation, drying of porous solids, and formation of ocean currents<sup>1</sup> occur due to thermal and solutal buoyancy forces developed as a result of difference in temperature or concentration or a combination of these two. Such configuration is also encountered in several practical systems for industry based applications viz. cooling of molten metals, heat exchanger devices, petroleum reservoirs, insulation systems, filtration, nuclear waste repositories, chemical catalytic reactors and processes, desert coolers, frost formation in vertical channels, wet bulb thermometers, etc. Considering the importance of such fluid flow problems, extensive and in-depth research works have been carried out by several researchers<sup>2-10</sup> in the past. Investigation of hydromagnetic natural convection flow with heat and mass transfer in porous and non-porous media has drawn considerable attentions of several researchers. Oreper and Szekely<sup>11</sup> have found that the presence of a magnetic field can suppress natural convection currents and the strength of magnetic field is one of the important factors in reducing non-uniform composition thereby enhancing quality of the crystal. Hossain and Mandal<sup>12</sup> investigated mass transfer effects on unsteady hydromagnetic free convection flow past an accelerated vertical porous plate. Jha<sup>13</sup> studied hydromagnetic free convection and mass transfer flow past a uniformly accelerated vertical plate through a porous medium when magnetic field is fixed with the moving plate. Elbashbeshy<sup>14</sup> discussed heat and mass transfer along a vertical plate in the presence of magnetic field. Chen<sup>15</sup> analyzed combined heat and mass transfer in MHD free convection flow from a vertical surface with Ohmic heating and viscous dissipation. Ibrahim *et al.*<sup>16</sup> considered unsteady MHD micropolar fluid flow and heat transfer past a vertical porous plate through a porous medium. Chamkha<sup>17</sup> investigated unsteady MHD convective flow with heat and mass transfer past a semi-infinite vertical permeable moving plate in a uniform porous medium with heat absorption. Makinde and Sibanda<sup>18</sup> investigated MHD mixed convection flow with heat and mass transfer past a vertical plate embedded in a uniform porous medium. Makinde<sup>19</sup> studied MHD mixed convection flow and mass transfer past a vertical porous plate embedded in a porous medium with constant heat flux. Eldabe *et al.*<sup>20</sup> discussed unsteady MHD flow of a viscous and incompressible fluid with heat and mass transfer in a porous medium near a moving vertical plate with time-dependent velocity. The unsteady hydromagnetic natural convection flow past a moving plate in a rotating medium is studied by a number of researchers such as the studies of Singh<sup>21,22</sup>, Raptis and Singh<sup>23</sup>, Kythe and Puri<sup>24</sup>, Tokis<sup>25</sup>, Nanousis<sup>26</sup> and Singh *et al.*<sup>27</sup>. Veera Krishna *et al.*<sup>28-29</sup> discussed the MHD flows through porous medium in planar channel. Krishna and M.G. Reddy<sup>30</sup> discussed the unsteady MHD free convection in a boundary layer flow of an electrically conducting fluid through porous medium subject to uniform transverse magnetic field over a moving infinite vertical plate in the presence of heat source and chemical reaction. Krishna and G.S. Reddy<sup>31</sup> have investigated the simulation on the MHD forced convective flow through stumpy permeable porous medium (oil sands, sand) using Lattice Boltzmann method. Krishna and K. Jyothi<sup>32</sup> discussed the Hall effects on MHD Rotating flow of a visco-elastic fluid through a porous medium over an infinite oscillating porous plate with heat source and chemical reaction. B.S.K. Reddy *et al.*<sup>33</sup> investigated MHD flow of viscous incompressible nano-fluid through a saturating porous medium.

In this paper, we have discussed the unsteady MHD natural convective rotating flow of an electrically conducting, viscous, incompressible and optically thick radiating second grade fluid past an impulsively moving vertical plate entrenched in a fluid inundated porous medium.

## 2. Formulation and Solution of the Problem :

We considered unsteady MHD natural convective flow of an electrically conducting, viscous,

incompressible and optically thick radiating fluid over an infinite vertical plate embedded in a uniform porous medium in a rotating system. The physical configuration of the problem is as shown in Fig. 1.

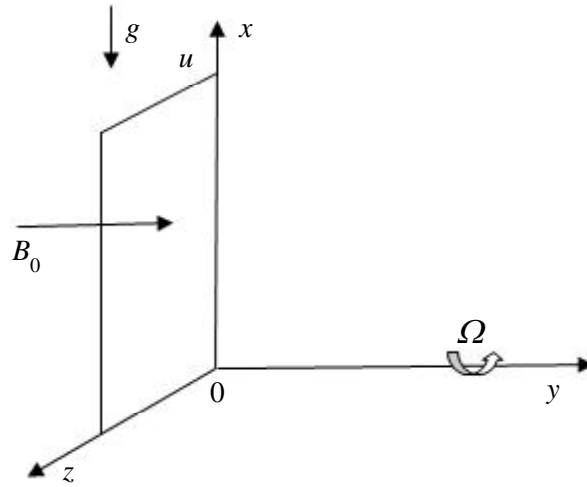


Fig 1. The physical configuration of the problem

Co-ordinate system is chosen,  $x$ -axis is along the plate in upward direction and  $y$ -axis normal to plane of the plate in the fluid. A uniform transverse magnetic field  $B_0$  is applied in a direction which is parallel to  $y$ -axis. The fluid and plate rotate in unison with uniform angular velocity  $\Omega$  about  $y$ -axis. Initially at  $t \leq 0$ , both the fluid and plate are at rest and are maintained at a uniform temperature. Concentration at the surface of the plate as well as at every point within the fluid is maintained at uniform concentration. At time  $t > 0$ , plate starts moving in  $x$ -direction with uniform velocity in its own plane. The temperature of plate is raised or lowered when  $0 < t \leq t_0$ , and it is maintained at uniform temperature when  $t > t_0$  ( $t_0$  being characteristic time). Also, at time  $t > t_0$ , species concentration at the surface of the plate is raised to uniform species concentration and is maintained thereafter. Since plate is of infinite extent in  $x$  and  $z$  directions, all physical quantities except pressure depend on  $y$  and  $t$  only.

The governing equations for flow through porous medium in a rotating frame under Boussinesq approximation, are given by

$$\frac{\partial u}{\partial t} + 2\Omega w = \nu \frac{\partial^2 u}{\partial y^2} + \frac{\alpha_1}{\rho} \frac{\partial^3 u}{\partial y^2 \partial t} - \frac{\sigma B_0^2}{\rho} u - \frac{\nu}{K_1} u + g\beta(\theta - \theta_\infty) + g\beta^*(\phi - \phi_\infty) \quad (1)$$

$$\frac{\partial w}{\partial t} - 2\Omega u = \nu \frac{\partial^2 w}{\partial y^2} + \frac{\alpha_1}{\rho} \frac{\partial^3 w}{\partial y^2 \partial t} + \frac{\sigma B_0^2}{\rho} w - \frac{\nu}{K_1} w \quad (2)$$

$$\rho C_p \frac{\partial \theta}{\partial t} = k \frac{\partial^2 \theta}{\partial y^2} - \frac{\partial q_r}{\partial y} \quad (3)$$

$$\frac{\partial \phi}{\partial t} = D \frac{\partial^2 \phi}{\partial y^2} \quad (4)$$

Initial and boundary conditions are

$$u = w = 0, \theta = \theta_\infty, \phi = \phi_\infty \text{ for } y \geq 0 \text{ and } t \leq 0, \quad (5)$$

$$u = U_0, w = 0 \text{ at } y = 0 \text{ for } t > 0, \quad (6)$$

$$\theta = \theta_\infty + (\theta_w - \theta_\infty) \frac{t}{t_0} \text{ at } y = 0 \text{ for } 0 < t \leq t_0, \quad (7)$$

$$\theta = \theta_w \text{ at } y = 0 \text{ for } t > t_0, \quad (8)$$

$$\phi = \phi_w \text{ at } y = 0 \text{ for } t > 0, \quad (9)$$

$$w \rightarrow 0; \theta \rightarrow \theta_\infty; \phi \rightarrow \phi_\infty \text{ as } y \rightarrow \infty \text{ for } t > 0. \quad (10)$$

For an optically thick fluid, emission and self-absorption we adopted the Rosseland approximation for radiative flux vector  $q_r$ ,

$$q_r = -\frac{4\sigma^*}{3k^*} \frac{\partial \theta^4}{\partial y}, \quad (11)$$

Assume small temperature difference between fluid temperature  $\theta$  and free stream temperature  $\theta_\infty$ ,  $\theta^4$  is expanded in Taylor series about free stream temperature to linearize equation (11), after neglecting second and higher order terms in  $\theta - \theta_\infty$ ,

$$\theta^4 \cong 4\theta_\infty^3 \theta - 3\theta_\infty^4. \quad (12)$$

Eq. (3) with help of Eqs. (11) and (12) reduces to

$$\frac{\partial \theta}{\partial t} = \frac{k}{\rho C_p} \frac{\partial^2 \theta}{\partial y^2} + \frac{1}{\rho C_p} \frac{16\sigma^* \theta_\infty^3}{3k^*} \frac{\partial^2 \theta}{\partial y^2} \quad (13)$$

We introduce the non-dimensional variables,

$$y^* = \frac{y}{U_0 t_0}, u^* = \frac{u}{U_0}, w^* = \frac{w}{U_0 t_0}, t^* = \frac{t}{t_0}, \theta^* = \frac{\theta - \theta_\infty}{\theta_w - \theta_\infty}, \phi^* = \frac{(\phi - \phi_\infty)}{(\phi_w - \phi_\infty)}$$

Making use of non-dimensional variables, Eqs. (1), (2), (4) and (13) are

$$\frac{\partial u}{\partial t} + 2R^2 w = \frac{\partial^2 u}{\partial y^2} + \alpha \frac{\partial^3 u}{\partial y^2 \partial t} - \frac{M^2}{(1+m^2)} (u + mw) - \frac{u}{K} + Gr\theta + Gc\phi \quad (14)$$

$$\frac{\partial w}{\partial t} - 2R^2 u = \frac{\partial^2 w}{\partial y^2} + \alpha \frac{\partial^3 w}{\partial y^2 \partial t} + \frac{M^2}{(1+m^2)} (mu - w) - \frac{w}{K}, \quad (15)$$

$$\frac{\partial \theta}{\partial t} = \frac{(1+N)}{P_c} \frac{\partial^2 \theta}{\partial y^2}, \quad (16)$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc} \frac{\partial^2 \phi}{\partial y^2}, \quad (17)$$

Where

$$M^2 = \frac{\sigma B_0^2 \nu}{\rho U_0^2} \text{ is the Hartmann number, } R^2 = \frac{\nu \Omega}{U_0^2} \text{ is the rotation parameter, } K = \frac{K_1 U_0^2}{\nu^2} \text{ is permeability parameter, } \alpha = \frac{U_0^2 \alpha_1}{\rho \nu^2} \text{ is the second grade fluid parameter, } Gr = \frac{g \beta \nu (\theta_w - \theta_\infty)}{U_0^3} \text{ is the thermal Grashof number, } Gc = \frac{g \beta^* \nu (\phi_w - \phi_\infty)}{U_0^3} \text{ is the mass Grashof number, } Pr = \frac{\nu \rho C_p}{k} \text{ Prandtl number}$$

$$N = \frac{16 \sigma^* \theta_\infty^3}{3 k k^*} \text{ thermal radiation parameter and } Sc = \frac{\nu}{D} \text{ is the Schmidt number.}$$

Characteristic time  $t_0$  is according to the non-dimensional process mentioned above as  $t_0 = \frac{\nu}{U_0^2}$ .

Combining Eqs. (14) and (15),

$$\frac{\partial F}{\partial t} = \frac{\partial^2 F}{\partial y^2} + \alpha \frac{\partial^3 F}{\partial y^2 \partial t} - \lambda F + Gr \theta + Gc \phi \quad (18)$$

Where  $F = u + iw$  and  $\lambda = M^2 + \frac{1}{K} - 2iR^2$ .

The non-dimensional boundary conditions are

$$F = 0, \theta = 0, \phi = 0 \text{ for } y \geq 0 \text{ and } t \leq 0 \quad (19)$$

$$F = 1 \quad \text{at } y = 0 \text{ for } t > 0, \quad (20)$$

$$\theta = t \quad \text{at } y = 0 \text{ for } 0 < t \leq 1, \quad (21)$$

$$\theta = 1 \quad \text{at } y = 0 \text{ for } t > 1, \quad (22)$$

$$\phi = 1 \quad \text{at } y = 0 \text{ for } t > 0, \quad (23)$$

$$F \rightarrow 0; \theta \rightarrow 0; \phi \rightarrow 0 \text{ as } y \rightarrow \infty \text{ for } t > 0. \quad (24)$$

Making use of Laplace transform technique, solving for the equations (16)–(18) and using initial and boundary conditions (19), we obtain the velocity, temperature and concentration fields for ramped and isothermal plates. Also, the skin friction components  $\tau_x$  and  $\tau_z$  and Nusselt number are evaluated for both ramped temperature plate and isothermal plates. The Sherwood number in terms of rate of mass transfer at the plate is also obtained.

### 3. Results and Discussion

We noticed that, Figs. 2 depict the influence of magnetic field on the primary velocity  $u$  and secondary velocity  $w$  for both ramped temperature and isothermal plates. It is evident from Figs. 2 that, for both ramped temperature and isothermal plates,  $u$  and  $w$  decreases on increasing Hartmann number  $M$  in a region near to the plate and the same nature the region away from the plate. Figs. 3 depict that both  $u$  and  $w$  are increase with increasing permeability parameter  $K$  throughout the fluid region. Lower the permeability lesser the fluid speed in the entire flow field. Figs. 4 illustrate the effects of rotation on the primary and secondary fluid velocities for both ramped temperature and isothermal plates. For both ramped temperature and isothermal plates,  $u$  decreases on increasing  $R$  whereas  $w$  increases on increasing  $R$  in the region near to the plate.

We also noticed from Fig. 5 that the temperature  $\theta$  increases with increasing  $N$  for both ramped temperature and isothermal plates. Thus thermal radiation be inclined to enhance fluid temperature throughout the boundary layer region in both cases. Hence thermal radiation offers diffuse energy, since an increase in  $N$  implies a decrease in Rosseland mean absorption coefficient  $k^*$  for fixed values of  $\theta_\infty$  and  $k$ . Also fluid temperature  $\theta$  decreases with increasing  $Pr$  whereas it boosts on increasing  $t$  in both cases. Therefore, in both cases, thermal diffusion tends to augment fluid temperature and there is an improvement in temperature with increase of time throughout the boundary layer region.

It is evident from Figs. 6 that species concentration  $\phi$  diminishes with increasing  $Sc$  whereas it enhances on increasing  $t$ . Therefore mass diffusion tends to increase concentration and there is an improvement in concentration with increase of time in entire fluid region.

The skin friction  $\tau_x$  increases and  $\tau_z$  decreases with increasing Hartmann number  $M$  for the ramped temperature, the reversal behaviour is observed for isothermal plate. For the ramped temperature and isothermal plates  $\tau_x$  reduces and  $\tau_z$  increases with increasing  $Gr$ ,  $Gc$ ,  $N$  and  $t$ , whereas  $\tau_x$  increases and  $\tau_z$  decreases with increasing  $Pr$  or  $Sc$ . Therefore, for ramped temperature and isothermal plates, thermal and concentration buoyancy forces, thermal and mass diffusions and thermal radiation have tendency to reduce  $\tau_x$  whereas these physical quantities have reverse effect on  $\tau_z$ . For the ramped temperature and isothermal plates  $\tau_x$  and  $\tau_z$  increases with increasing rotation parameter  $R$  or second grade fluid parameter  $\alpha$ . Rotation tends to enhance both  $\tau_x$  and  $\tau_z$  for both ramped temperature and isothermal plates. Both  $\tau_x$  and  $\tau_z$  are increase for the ramped temperature and decrease for isothermal plate on increasing permeability parameter  $K$ . The rate of heat transfer reduces with increasing  $N$  and is augmented on increasing time for both cases, whereas it is diminished initially and then increases with the growth of  $Pr$ . The Schmidt number to enhance rate of mass transfer at the plate and there is refuse in rate of mass transfer at the plate on increasing time.

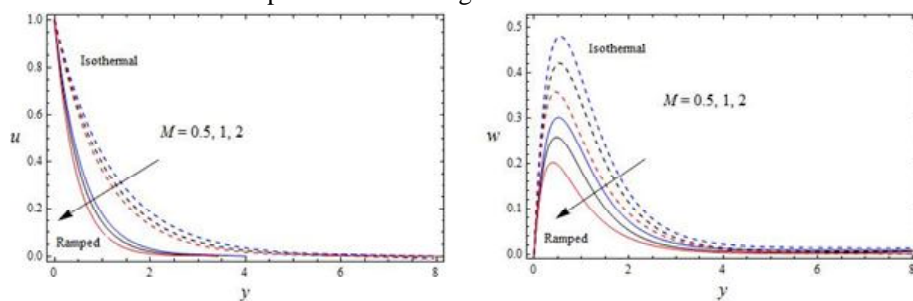


Fig. 2 The velocity profiles for  $u$  and  $w$  against  $M$  with

$$R = 1, K = 0.5, m = 1, \alpha = 1, Pr = 0.71, N = 1, Sc = 0.22, Gr = 3, Gc = 5, t = 0.2$$

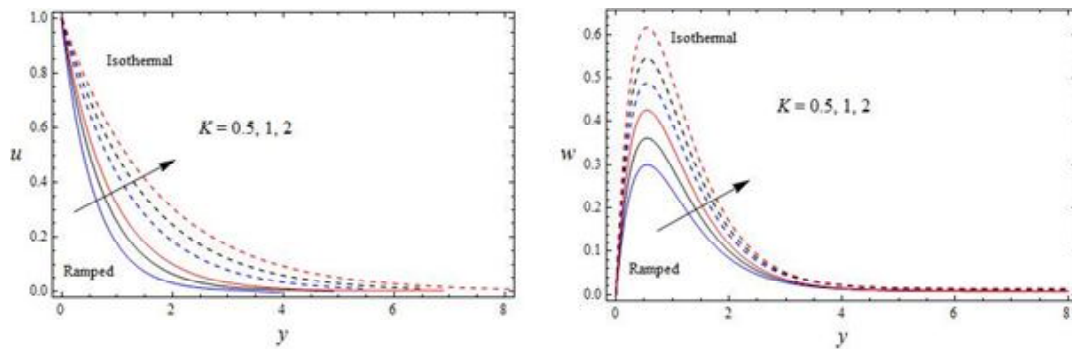


Fig. 3 The velocity profile for  $u$  and  $w$  against  $K$  with  $M = 0.5, R = 1, m = 1, \alpha = 1, Pr = 0.71, N = 1, Sc = 0.22, Gr = 3, Gc = 5, t = 0.2$

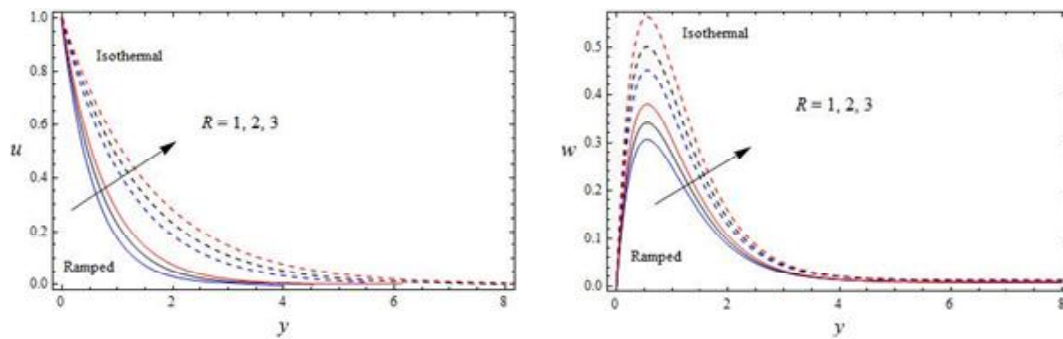


Fig. 4 The velocity profile for  $u$  and  $w$  against  $R$  with  $M = 0.5, K = 0.5, m = 1, \alpha = 1, Pr = 0.71, N = 1, Sc = 0.22, Gr = 3, Gc = 5, t = 0.2$

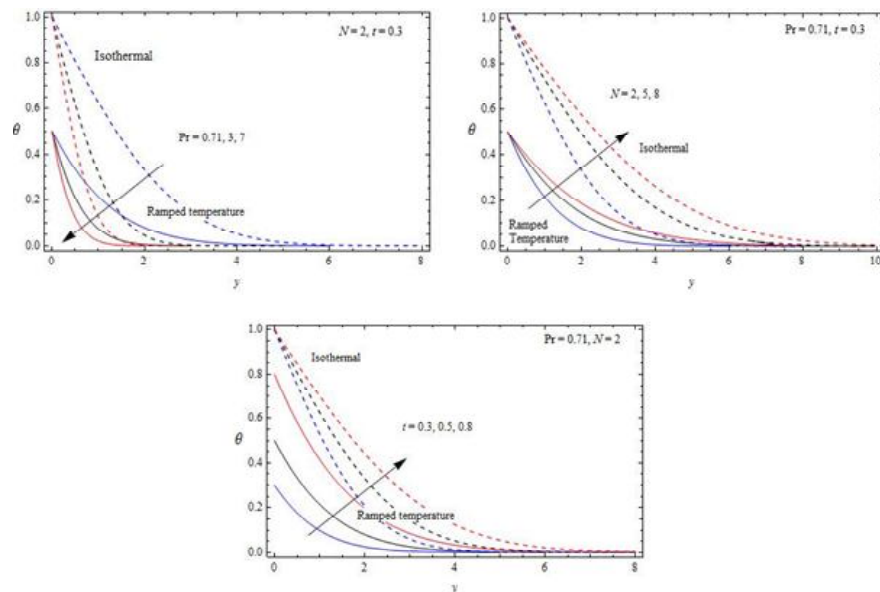


Fig. 5 The temperature profile against  $Pr, N$  and  $t$



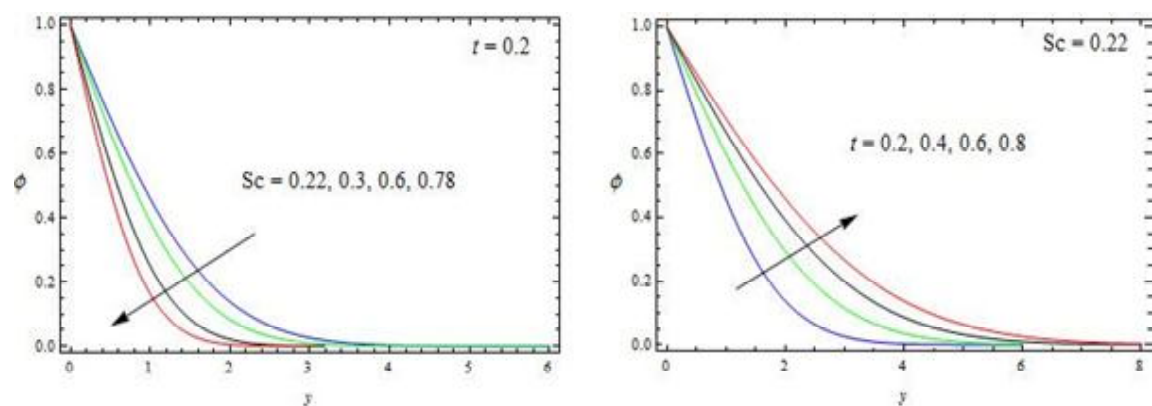


Fig. 6 The concentration profile against  $Sc$  and  $t$

Table 1: Skin friction

$M$	$K$	$R$	$\alpha$	$Pr$	$Gr$	$Gc$	$N$	$Sc$	$t$	Ramped temperature $-\tau_x$	$\tau_z$	Isothermal plate $-\tau_x$	$\tau_z$
0.5	0.5	1	1	0.71	3	5	2	0.22	0.2	2.85588	1.98855	2.18559	2.41744
1										3.14541	1.54855	1.85985	2.66011
1.5										3.41985	1.35895	1.70415	2.87748
	1									3.25452	2.32512	1.70859	1.85748
	1.5									3.64693	2.66855	1.24141	1.41744
		2								3.25855	2.14415	2.48014	2.85785
		3								3.65212	2.58966	2.87963	3.22441
			2							3.11142	2.29001	2.47478	2.88478
			3							3.52996	2.62963	2.80856	3.14774
										2.45784	2.22741	1.89748	2.66123
										2.22411	2.55785	1.52774	2.99785
				3						3.32200	1.82996	2.33784	2.22652
				7						3.66985	1.70144	2.61410	2.01325
					4					2.56744	2.33966	2.05744	2.66633
					5					2.01415	2.50771	1.88885	2.80485
						6				2.45520	2.15147	1.88962	2.85633
						7				2.14969	2.36885	1.52321	3.21023
							3			2.71415	1.99623	2.01747	2.45749
							4			2.60475	2.00251	1.89874	2.47965
								0.3		2.99477	1.80145	2.35147	2.22256
								0.6		3.14855	1.65366	2.52774	2.01693
									0.5	2.71748	2.13785	2.01114	2.89874
									0.8	2.51450	2.41859	1.89415	3.20089

Table 2: Nusselt number

$N$	$Pr$	$t$	$Nu$ Ramped temperature	$Nu$ Isothermal plate
2	0.71	0.5	0.274469	0.194079
5			0.194079	0.137235
8			0.158465	0.112052
	3		0.164682	0.150333
	7		0.439151	0.245493
		0.3	0.564190	0.398942
		0.8	0.861814	0.609394

Table 3: Sherwood number

$Sc$	$t$	$Sh$
0.22	0.2	-0.591727
0.3		-0.690988
0.6		-0.977205
0.78		-1.114190
	0.4	-0.418414
	0.6	-0.341634
	0.8	-0.295864

#### 4. Conclusions

For both ramped temperature and isothermal plates, Rotation tends to accelerate  $w$  and decelerate  $u$  throughout the boundary layer region. Thermal radiation and thermal diffusion tends to enhance fluid temperature throughout the boundary layer region. Mass diffusion tends to enhance concentration throughout the boundary layer region. Rotation and second grade fluid parameter tend to enhance  $\tau_x$  and  $\tau_z$ . Primary skin friction is getting reduced whereas secondary skin friction is getting enhanced with the progress of time.  $Nu$  reduces with increasing  $N$  and is augmented on increasing time. The Schmidt number to enhance  $Sh$  at the plate and refuse on increasing time.

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