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NUMERICAL STUDY OF MHD DOUBLE DIFFUSIVE ROTATING FLOW OVER A VERTICAL POROUS PLATE IN THE PRESENCE OF HEAT SOURCE/SINK

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ABSTRACT

*This paper is devoted to introduce a numerical study of an unsteady double diffusive flow over an impulsively emerged vertical porous plate in fluctuating temperature and mass diffusion in the presence of heat source/sink. A magnetic field is applied normal to the flow. The governing equations in non-dimensional form are solved numerically, using Crank-Nicholson method and the simulation is carried out by coding in **C-Program**. Graphical results for velocity, temperature and concentration fields and tabular values of Nusselt number are presented and discussed at various parametric conditions. From this study, it is found that Nusselt number, temperature and velocity of the fluid increase in the presence heat source while reverse effect is noted in the presence of heat sink. Thermal radiation reduces the velocity and temperature of the fluid. The results which are obtained for Nusselt number in the absence/presence heat source and sink are almost tallied with previously published data.*

Keywords: *Double diffusive fluid; Rotation; MHD; Porous medium; Radiation; Finite-difference meyhod.*

1. INTRODUCTION

In the recent years, the problem of hydrodynamic laminar flow through a porous medium has become very significant because of its possible applications in many branches science and technology [1-4]. Actually, many processes in engineering areas occur at high temperature and therefore knowledge of radiation heat transfer becomes very important for the design of the pertinent equipment. Also convective flows with radiation encountered in many environmental and engineering processes, for example, evaporation from large open reservoirs, gas turbines and the various propulsion devices for air craft heating and cooling chambers, astrophysical flows, solar control technology and space vehicle re-entry.

Sharma *et al.* [5] studied the influence of homogeneous chemical reaction and radiation on unsteady magneto-hydrodynamic free convection flow of a viscous incompressible flow past a heated vertical plate immersed in porous medium in the presence of heat source. Reddy *et al*. [6] have discussed the unsteady hydromagnetic radiative and chemically reactive free convection flow near the moving vertical plate in porous medium. Several authors [7-18] have addressed different issues related to thermal radiation. Double-diffusive convection is a necessary process in oceanography and it plays a role in mantle convection (magma chambers) and in some technological applications. Bakr and Riazahb [19], Mohamed [20], Awad *et al.* [21], Hayat *et al*. [22] focused on some double diffusive free-convective flow problems. Remarkable contributions associated to rotating fluid and mass transfer are reported by many researchers [23–32]. Recently, Ram Prakash Sharma *et al.* [33] studied the **r**otational impact on unsteady double diffusive flow over an impulsively emerged vertical porous plate in fluctuating temperature and mass diffusion in the presence of uniform transversely applied magnetic field. More recently, unsteady MHD free convection flow, heat and mass transfer past an exponentially accelerated inclined plate embedded in a saturated porous medium with uniform permeability, variable temperature and concentration is analyzed by Jyotsna Rani Pattnaik *et al.* [34].

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In most of the earlier unsteady MHD double diffusive flow problems, the effect heat source/sink has not been considered. But it plays an essential role in maintaining the heat transfer at desired level in the fields of gas turbines, Nuclear power plants, and the various propulsion devices for aircraft, missiles, satellites and space vehicles. Due to the coupled non-linearity of the problem, in the most of the previous researches, analytical or perturbation methods were adopted to obtain the solution of the problem. However, in the present paper a numerical attempt is made to study an unsteady MHD double diffusive flow over an impulsively emerged vertical porous plate in fluctuating temperature and mass diffusion in the presence of heat source/sink. A magnetic field of uniform strength is applied normal to the fluid flow. In order to obtain the approximate solution and to describe the physics of the problem, the present non-linear boundary value problem is solved numerically using implicit finite difference formulae known as Crank-Nicholson method.

4. FORMULATION OF THE PROBLEM

An unsteady flow of an electrically conducting fluid induced by viscous incompressible fluid past an impulsively started vertical porous plate with mass transfer and variable temperature is considered. The fluid and the plate rotate as a rigid body with an identical angular velocity Ω^* about y^* -axis in the presence of an imposed uniform magnetic field B_0, normal to the plate. Initially, the concentration and temperature of the fluid near the plate are assumed to be T_∞^* and C_∞^* respectively. At $t^* > 0$ the plate starts moving with a velocity $u^* = u_0$ in its own plane and the temperature and concentration levels near the plate are raised linearly with respect to time. Since the plate occupying the plane $y^* = 0$ is of infinite extent, all the material quantities depend only on y^* and t^* . It is assumed that the induced magnetic field is negligible so that $\vec{B} = (0,0,B_0)$. Followed by the above assumptions and from the results of Rajput [23], the governing equations are given below.

$$\frac{\partial u'}{\partial t'} - 2\Omega' v' = g\beta\upsilon(T_w' - T_\infty') + g\beta^*\upsilon(C_w' - C_\infty') + \upsilon\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2 u'}{\rho} \quad (1)$$

$$\frac{\partial v'}{\partial t'} + 2\Omega' u' = \upsilon\frac{\partial^2 v'}{\partial y'^2} - \frac{\sigma B_0^2 v'}{\rho} \quad (2)$$

$$\rho C_p\frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} + S'(T' - T_\infty') \quad (3)$$

$$\frac{\partial C'}{\partial t'} = D_M\frac{\partial^2 C'}{\partial y^2} + \frac{D_M K_T}{T_M}\frac{\partial^2 T'}{\partial y'^2} \quad (4)$$

The boundary conditions suggested by the physics of the problem are

$$\begin{aligned} &t' \le 0; u' = 0, T' = T_\infty', \ C' = C_\infty', \text{ for all the values of } y' \\ &t' > 0: u' = u_0, v^* = 0,\ T' = T_\infty' + (T_w' - T_\infty'),\ C' = C_\infty' + (C_w' - C_\infty') \ \text{ at } \ y' = 0 \\ &u' \to 0,\ v^* = 0,\ T' \to T_\infty',\ C' \to C_\infty', \ \text{ as } \ y' \to \infty \end{aligned} \quad (5)$$

Here the fluid considered as a gray, absorbing/ emitting radiation but a non-scattering medium. The local gradient for the case of an optically thin gray gas [35] is expressed by

$$\frac{\partial q_r}{\partial y'} = -4a^*\sigma(T_\infty'^4 - T'^4) \quad (6)$$

It has been assumed that the temperature differences within the flow are sufficiently small and T'^4 may be expressed as a linear function of the temperature T'. This is accomplished by expanding T'^4 in a Taylor series about, T_∞' as follows.

Let $f(T') = f(T_\infty') + (T' - T_\infty')f'(T_\infty') + \frac{(T' - T_\infty')^2}{2!}f''(T_\infty') + \cdots$ (7)
where, $f(T') = T'^4, f'(T') = 4T'^3$

Neglecting the higher order terms in (7),we get

$$T'^4 \approx 4T_\infty'^3 T' - 3T_\infty'^4 \quad (8)$$

Using (8) in (6) and then (6) in (3), we get

$$\rho C_p\frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial y'^2} - 16a^*\sigma T_\infty'^3(T' - T_\infty') + S'(T' - T_\infty') \quad (9)$$

Introducing the following non-dimensional quantities

$$u = \frac{u'}{u_0},\ v = \frac{v'}{v_0}, t = \frac{t' u_0^2}{\upsilon}, y = \frac{y' u_0}{\upsilon}, \phi = \frac{(C' - C_\infty')}{(C_w' - C_\infty')}, T = \frac{(T' - T_\infty')}{(T_w' - T_\infty')}$$

$$Gr = \frac{g\beta\upsilon(T_w' - T_\infty')}{u_0^3}, Gm = \frac{g\beta^*\upsilon(C_w' - C_\infty')}{u_0^3}, \Omega = \frac{\Omega^*\upsilon}{u_0^2}, \mathrm{So} = \frac{D_M K_T(T_w' - T_\infty')}{\upsilon T_M(C_w' - C_\infty')}$$

$$M = \frac{\sigma B_0^2\upsilon}{\rho u_0^2},\ Sc = \frac{\upsilon}{D},\ Pr = \frac{\mu C_p}{k},\ N = \frac{16a^*\upsilon^2\sigma T_\infty'}{k u_0^2},\ S = \frac{S'\upsilon}{\rho C_p u_0^2}$$

In to equations (1), (2), (4) and (9), we get the following equations in non-dimensional form:

$$\frac{\partial u}{\partial t} - 2\Omega v = Gr\theta + Gm\phi + \frac{\partial^2 u}{\partial y^2} - Mu \tag{10}$$

$$\frac{\partial v}{\partial t} + 2\Omega u = \frac{\partial^2 v}{\partial y^2} - Mv \tag{11}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} - \frac{N}{Pr}\theta + S\theta \tag{12}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} + So\frac{\partial^2 \theta}{\partial y^2} \tag{13}$$

with boundary conditions

$$\begin{aligned} &t \le 0;\ u = 0, \theta = 0, \phi = 0 \ \text{ for all the values of y} \\ &t > 0:\ u = 1, \theta = t, v = 0, \phi = t \ \text{ at } y = 0 \\ &u \to 0, \theta \to 0, v = 0, \phi \to 0 \ \text{ as } y \to \infty \end{aligned} \tag{14}$$

5. METHOD OF SOLUTION

The equations (10)-(13) are coupled, non-linear partial differential equations whose exact solution is difficult to obtain. So substituting following finite difference formulae

$$\frac{\partial f}{\partial t} = \frac{f_i^{j+1} - f_i^j}{\Delta t}, \quad \frac{\partial f}{\partial y} = \frac{f_{i+1}^j - f_i^j}{\Delta y},$$

$$\frac{\partial^2 f}{\partial y^2} = \frac{1}{2}\left(\frac{f_{i-1}^j - 2f_i^j + f_{i-1}^j}{(\Delta y)^2} - \frac{f_{i-1}^{j+1} - 2f_i^{j+1} + f_{i-1}^{j+1}}{(\Delta y)^2}\right)$$

In to the equations (10) to (13) and simplifying implicitly according to the **Crank-Nicholson method**, we get the following system of equations

$$-\frac{r}{2}u_{i-1}^{j+1} + (1+r)u_i^{j+1} - \frac{r}{2}u_{i+1}^{j+1} = a_i^j \tag{15}$$

$$-\frac{r}{2}v_{i-1}^{j+1} + (1+r)v_i^{j+1} - \frac{r}{2}v_{i+1}^{j+1} = b_i^j \tag{16}$$

$$-\frac{r}{2Pr}\theta_{i-1}^{j+1} + (1+\frac{r}{Pr})\theta_i^{j+1} - \frac{r}{2Pr}\theta_{i+1}^{j+1} = d_i^j \tag{17}$$

$$-\frac{r}{2Sc}\phi_{i-1}^{j+1} + (1+\frac{r}{Sc})\phi_i^{j+1} - \frac{r}{2Sc}\phi_{i+1}^{j+1} = e_i^j \tag{18}$$

with boundary conditions in finite difference form

$$\begin{aligned} &u(i,j) = 0, \theta(i,j) = 0, \phi(i,j) = 1 \ \text{ for all } i,j \\ &u(0,j) = 0, \theta(0,j) = jk, \phi(i,j) = jk\ \forall\ j \\ &u(\infty,j) \to 0, \theta(\infty,j) \to 0, \phi(\infty,j) \to 0\ \forall\ j \end{aligned} \tag{19}$$

Where, f stands $u, \theta, v, \phi,$ and $r = \Delta t/(\Delta y)^2$,

$$a_i^j = \frac{r}{2}u_{i-1}^j + (1 - r + M\Delta t)u_i^j + \frac{r}{2}u_{i+1}^j + \Delta t(Gr\theta_i^j + Gm\phi_i^j)$$

$$b_i^j = \frac{r}{2}v_{i-1}^j + (1 - r + M\Delta t)v_i^j + \frac{r}{2}v_{i+1}^j$$

$$d_i^j = \frac{r}{2Pr}\theta_{i-1}^j + \left(1 - \frac{r}{Pr} - \frac{N\Delta t}{Pr}\right)\theta_i^j + \frac{r}{2Pr}\theta_{i+1}^j$$

$$e_i^j = \frac{r}{2Sc}\phi_{i-1}^j + \left(1 - \frac{r}{Sc}\right)\phi_i^j + \frac{r}{2Sc}\phi_{i+1}^j + So\left(\frac{\theta(i-1) - 2\theta(i) + \theta(i+1)}{h^2}\right)$$

Here Δy and Δt are mesh sizes along y and time t direction, respectively. Index i refers to space and j for time.

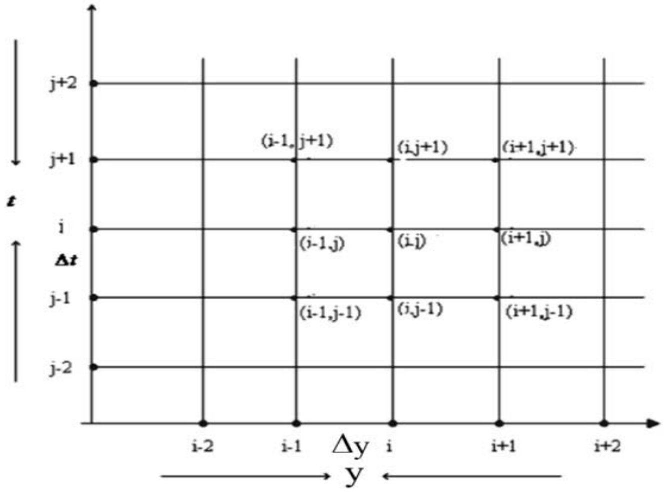

Figure-4.3.1: Grid meshing for finite-difference scheme

To obtain the difference equations, the region of the flow is divided into a grid or mesh of lines parallel to y *and* t axes as shown in the figure. The finite-difference equations at every internal nodal point on a particular n-level constitute a tri-diagonal system of equations. So, in the equations (15) to (18), taking $i = 1(1)n$ and using the boundary conditions (19), the following tri-diagonal system of equations are obtained.

$$DU = A \tag{20}$$
$$ET = H \tag{21}$$
$$FC = G \tag{22}$$
$$MN = R \tag{23}$$

Where D, E, F and M are the tri-diagonal matrices of order n whose elements are defined by

$$D_{i,i} = B_1,\ E_{i,i} = B_2,\ F_{i,i} = B_3,\ M_{i,i} = B_4,\ for\ i = 1(1)\ n$$
$$D_{i-1,i} = A_1, E_{i-1,i} = A_2,\ F_{i-1,i} = A_3,\ M_{i-1,i} = A_4,\ for\ i = 2(1)\ n$$
$$D_{i,i-1} = A_1, E_{i,i-1} = A_2,,\ F_{i,i-1} = A_3,\ M_{i,i-1} = A_4\ for\ i = 2(1)\ n$$

and U, A, T, H, C, G,N and R are column matrices having n components, namely

$u_i^{j+1}, a_i^j, v_i^{j+1}, b_i^j, \theta_i^{j+1}, d_i^j, \phi_i^{j+1}, e_i^j; i = 1(1)n$, respectively.

The above tri-diagonal system is solved by using the Thomas algorithm [18], for which a numerical simulation is carried out by coding in C-Program. In order to prove the convergence of present numerical scheme, the computation is carried out by slightly changed values of Δy **and** Δt and the iterations on until a tolerance 10^{-8} is attained. No significant change is observed in the values of u, v, θ *and* ϕ. Thus, it is concluded that the finite difference scheme is convergent and stable.

Nusselt number

The rate of heat transfer at the plate in terms of Nusselt number is given by

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

RESULTS AND DISCUSSION

In order to get the physical understanding of the problem and to investigate the significance of the various physical parameters involved in this study, a parametric study of the physical parameters is conducted. In this article, an unsteady MHD double diffusive rotational flow over an impulsively emerged vertical porous plate in fluctuating temperature and mass diffusion in the presence of heat source/sink is investigated numerically.

The primary and secondary velocity profiles for various values of the Magnetic parameter M is exhibited in the figures (1) and 2), (8) and (10) respectively. Magnetic parameter M describes the ratio of electromagnetic force to the viscous force. It is observed from the figure that the primary velocity decreases and secondary velocity increases with an increase in Magnetic parameter. This is due to fact that the interaction of the magnetic field with an electrically conducting fluid produces a body force known as Lorentz force, which plays the role of a resistive type force on the primary velocity and this force acts against to the fluid flow when the magnetic field is applied perpendicular to it. Therefore it is likely to suppress the flow thereby declining the primary velocity. On the other hand, an opposed effect is observed in the case of secondary velocity in the presence of magnetic parameter as the resulting Lorentz force acts as an aiding body force on the secondary flow.

Figures (3) and (7) demonstrate the effect of rotation on the primary and secondary fluid velocities respectively. It is evident from figures that primary velocity u decreases with the increasing values of Ω but there is an enhancement in the secondary flow velocity is observed on increasing Ω. This implies that rotation slows down the fluid flow in the main flow direction and increase speed of the fluid flow in the secondary flow direction in the boundary layer region. This is due to the fact that when the frictional layer at the moving plate is suddenly set into the motion, then the Coriolis force acts as a constraint in the primary flow direction to generate cross flow i.e. secondary flow.

The effect of heat source and sink parameter on primary and secondary velocities is shown in figures (4) and (9) respectively while the effect of heat source and sink on temperature field is exhibited by the curves in figures (11) and (14) respectively. It is evident that the temperature and velocity increase with the increasing values of heat source parameter. This result qualitatively concurs with the physical reality that heat generation is to boost up the rate of heat transport to the fluid there by growing the temperature of the fluid. Thus, the presence of heat source is found to be favorable in enhancing the velocity. It is also noted that temperature and velocity of the fluid reduce in the presence of heat sink as heat absorption is to decline the rate of heat transfer to the fluid.

Figures (5) and (12) show the effect of thermal radiation N on primary velocity and temperature respectively. It is obvious from figures that, the thermal radiation leads to reduce the velocity and temperature of the fluid. This due to the fact that an increase in the thermal radiation leads to decline in the rate of radiative heat, transferred to the fluid. So it causes a reduce in kinetic energy of the fluid particles. This consequence leads to decrease in the velocity and temperature of the fluid. Now, from these figures, it is observed that radiation has a more considerable effect on temperature than on primary velocity.

Figures (6) and (15) show the effect of Soret number on primary velocity and concentration respectively. A comparative study of the graph reveals that the velocity and temperature of the fluid increase with the increasing values of Soret number So. This means that Soret number accelerate the primary velocity of the flow throughout the boundary layer. Growing Soret number demonstrates a reduce in the viscosity of the fluid. It leads to enhanced inertia effects and weakened viscous effects. Consequently the concentration and velocity of the fluid increase. Fig (13) depicts the temperature profile for various values of Pr. This graph reveals that the presence of high Prandtl number is found to slow down the temperature of the fluid at all points. This is due to the physical fact that a fluid with high Prandtl number has a relatively low thermal conductivity. Table (1) shows the Nusselt number in both in presence and absence of heat source. It is observed that Nusselt number increase in the presence of heat source parameter.

In order to access the validity of the present numerical scheme, the present results are compared with previous published data [33] for Nusselt number in the absence of heat source parameters. The results of the validation of the present work agree significantly.

5. CONCLUSIONS

Unsteady MHD double diffusive rotational flow over an impulsively emerged vertical porous plate in fluctuating temperature and mass diffusion in the presence of heat source/sink is analyzed numerically. From this study the following conclusions are drawn.

1. The temperature and velocity of the fluid increase in the presence heat source but reverse effect is noted in the presence heat sink. Nusselt number also increase in the presence of heat source.
2. An increase in So leads to increase in the velocity and concentration but an increase in M leads to decrease in the velocity. Primary velocity u reduces while secondary velocity v increases with the growing values of rotational parameter Ω.
3. The effect of heat source/sink on temperature is more significant than in the case of velocity field.
4. The results of the validation of this work in the absence of heat source parameter agree significantly with previous work [33].

Table-1: Nusselt number (Nu)

Pr	N	Nu when S=0.0 **Ram Prakash Sharma** et al [33]	Nu when S=2.0 Present result
0.71	1	2.4484	2.8641
7.0	1	4.7226	4.9254
0.71	0.1	2.6629	2.8764
0.71	0.1	2.4860	2.6860

NOMENCLATURE

C'_∞	Concentration in the fluid far away from the plate
C'_w	Concentration of the fluid near the plate
T'_∞	Temperature of the fluid far away from the plate
T'_w	Constant temperature of the plate
S'	Constant heat source
t'	Dimensional time
t	Dimensionless time
D_M	Coefficient of mass diffusivity
T'	Temperature of the plate
K_T	Thermal diffusion ratio
T_M	The mean fluid temperature
g	Acceleration due to gravity
C_p	Specific heat at constant pressure,
u'	Primary velocity of the fluid
Gr	Grashof number

u	Dimensionless velocity along x - axis
Gm	Modified Grashof number
a^*	Absorption coefficient
v'	Secondary velocity of the fluid
M	Magnetic parameter
v	Dimensionless velocity along y-axis
q_r	Radiative heat flux
y'	Coordinate axis normal to the plate
Sc	Schmidt number
Pr	Prandtl number
β^*	Volumetric coefficient of expansion for concentration
β	Volumetric coefficient of thermal expansion
Ω	dimensionless rotation parameter
σ	Stefan-Boltzmann constant
k	Thermal conductivity of the fluid
ρ	density of the fluid
υ	Kinematic viscosity
Ω^*	dimensionless rotational parameter
μ	Coefficient of viscosity
N	Radiative parameter
B_0	Magnetic field strength
S	Heat source/sink parameter

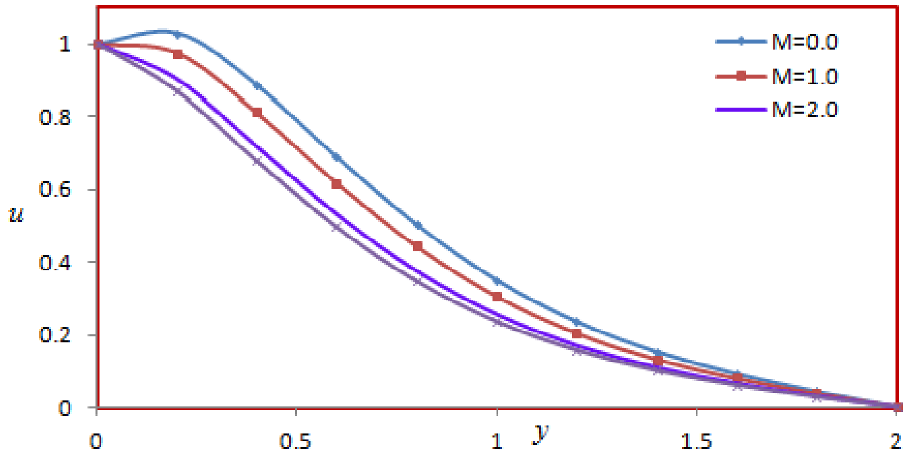

Figure-1: Effect of magnetic parameter M on Primary velocity u
t=1.0; Gm=5; K=0.1; N=0.1; Gr=5; Sc=0.22; Ω=0.5; Pr=0.71

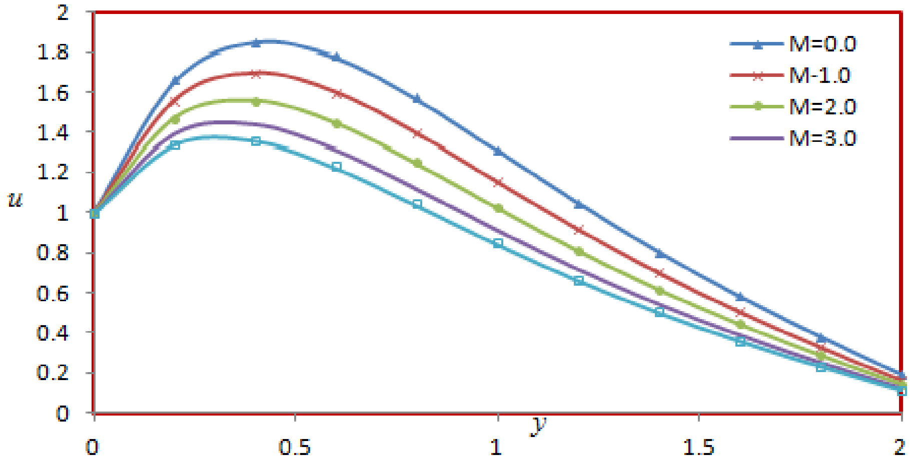

Figure-2: Effect of magnetic parameter M on Primary velocity u
(t=2; Gm=5; K=0.1; N=0.1; Gr=5;Sc=0.22; Ω=0.5; Pr=0.71)

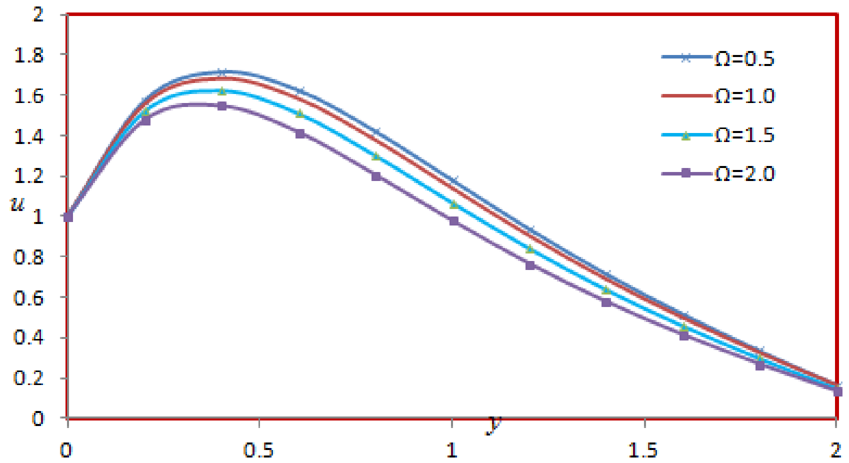

Figure-3: Effect of rotational Ω on Primary velocity u
(t=2; Gm=5; K=0.1; N=0.1; Gr=5; Sc=0.22; S=0.5; Pr=0.71)

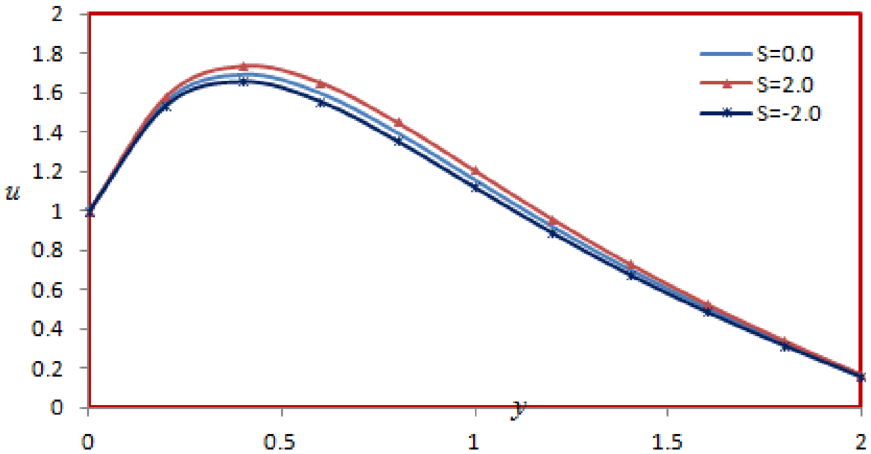

Figure-4: Effect of heat source /sink on Primary velocity u
(t=2; Gm=5; K=0.1; N=0.1; Gr=5; Sc=0.22; Ω =0.5; Pr=0.71)

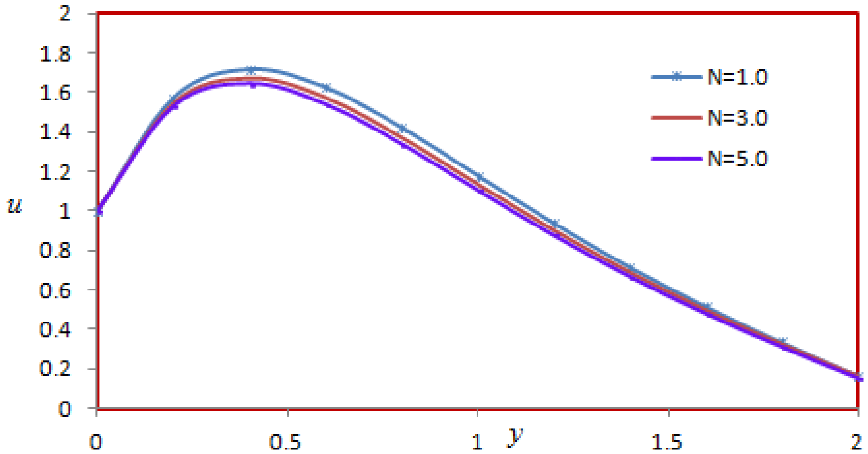

Figure-5: Effect of Radiation on Primary velocity u
(t=2; Gm=5; K=0.1;S=0.5; Gr=5; Sc=0.22; Ω =0.5; Pr=0.71)

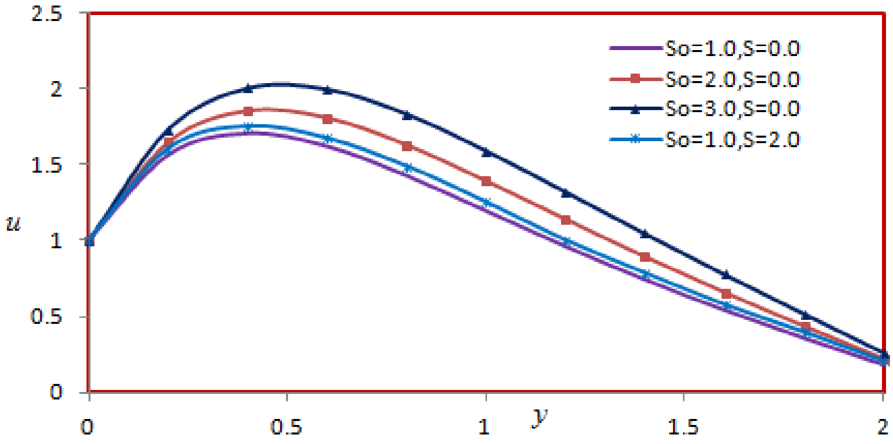

Figure- 6: Effect of Soret in the presence of heat source /sink on Primary velocity u
(t=2; Gm=5; K=0.1; N=0.1; Gr=5; Sc=0.22; Ω =0.5; Pr=0.71)

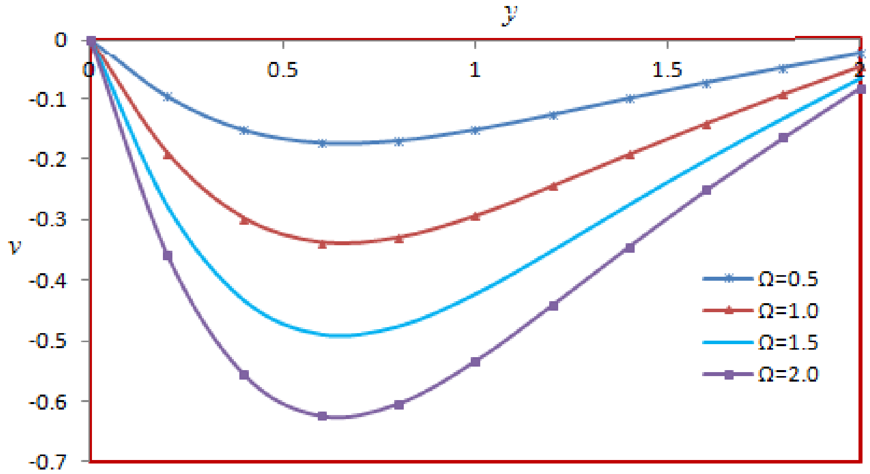

Figure-7: Effect of rotational Ω on secondary velocity u
(t=2; Gm=5; K=0.1; N=0.1; Gr=5; Sc=0.22; S=0.5; Pr=0.71)

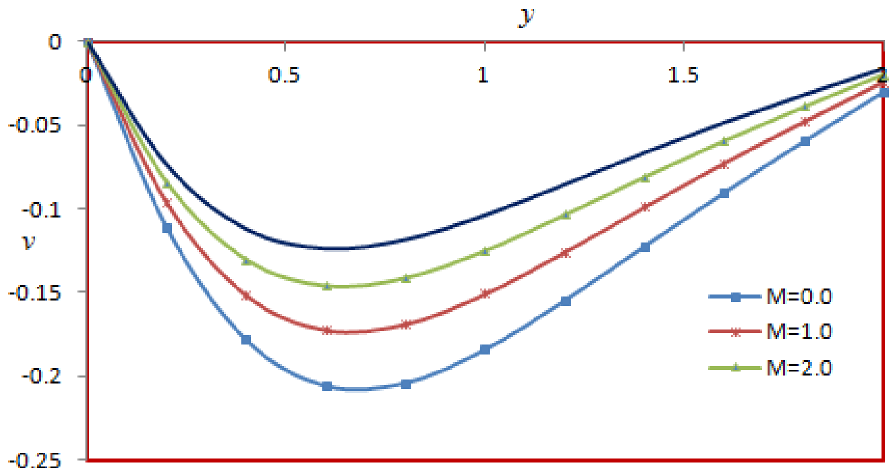

Figure-8: Effect of magnetic parameter M on secondary velocity u
(t=1; Gm=5; K=0.1; N=0.1; Gr=5; Sc=0.22; Ω=0.5; Pr=0.71)

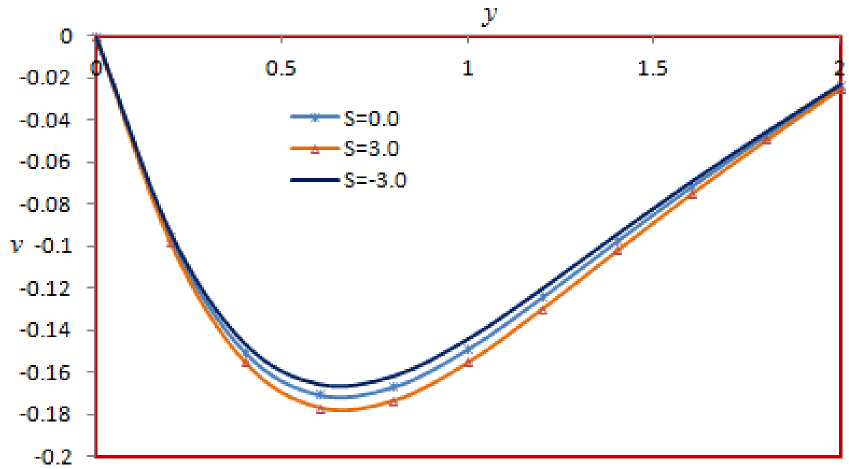

Figure-9: Effect of heat source /sink on secondary velocity u
(t=2; Gm=5; K=0.1; N=0.1; Gr=5; Sc=0.22; Ω =0.5; Pr=0.71)

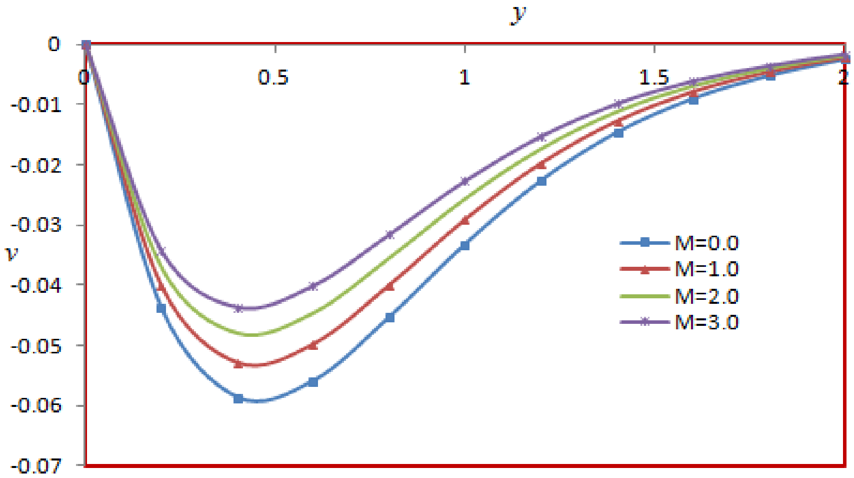

Figure-10: Effect of magnetic parameter M on secondary velocity u
(t=2; Gm=5; K=0.1; N=0.1; Gr=5; Sc=0.22; Ω=0.5; Pr=0.71)

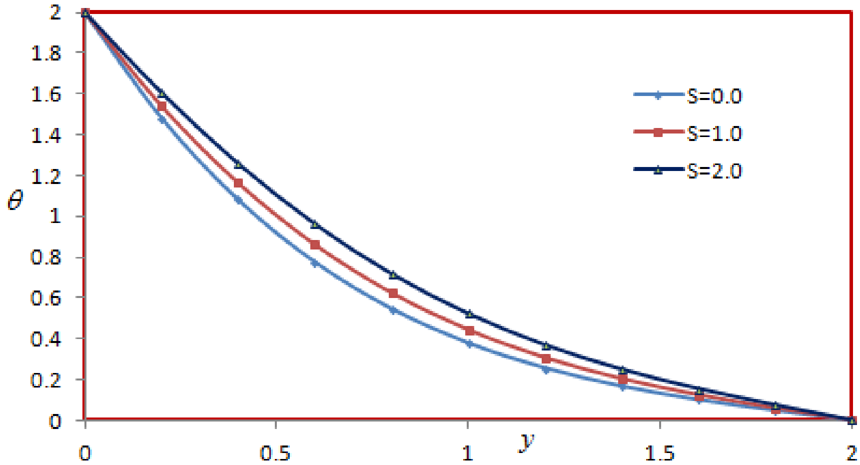

Figure-11: Effect of heat source on temperature field
(t=2; N=0.1; Pr=0.71)

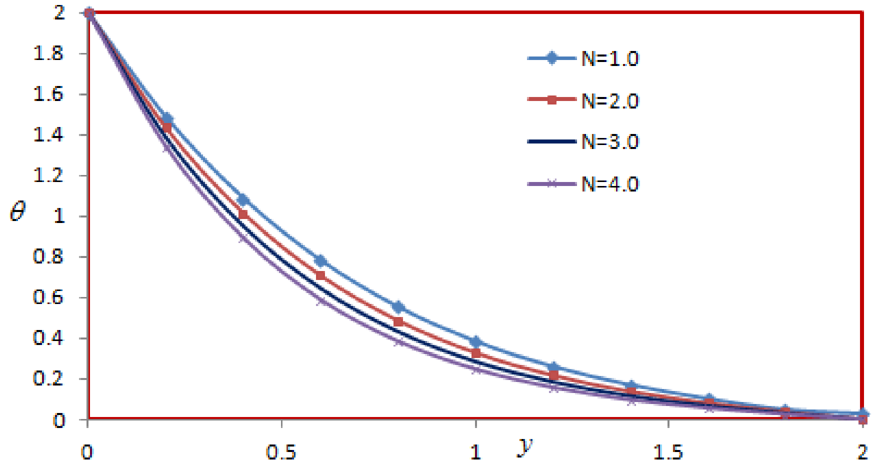

Figure-12: Effect of radiation on temperature field
(t=2; S=0.5; Pr=0.71)

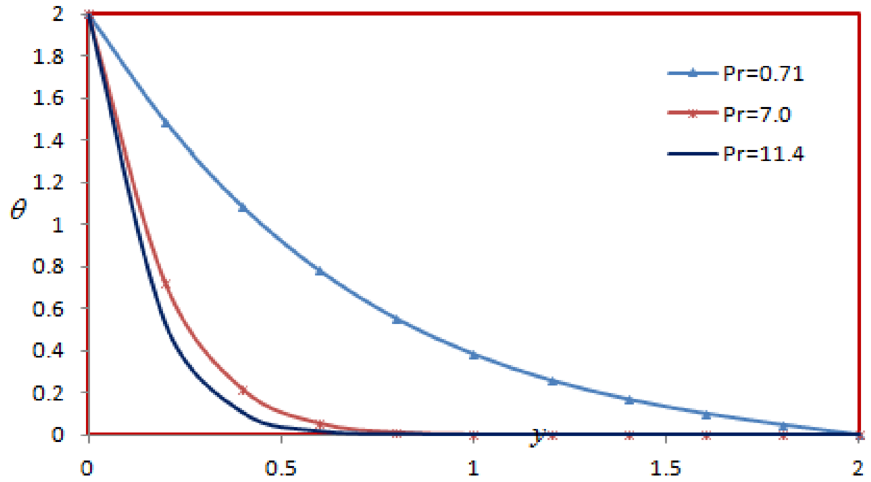

Figure-13: Effect of Prandtl number on temperature field
(t=2; N=0.5; S=0.5)

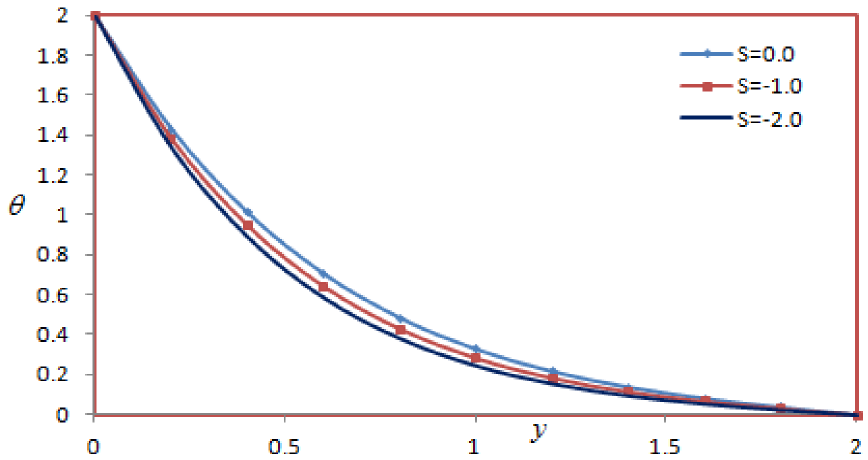

Figure-14: Effect of heat sink on temperature field
(t=2; N=0.1; Pr=0.71)

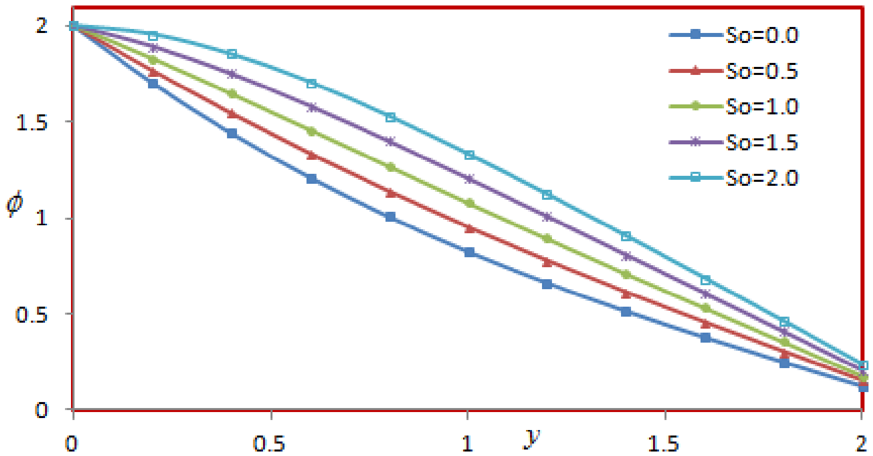

Figure-15: Effect of Soret on Concentration field
(t=2; Sc=0.22)

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