



Soret Effect on Unsteady MHD Free Convection Flow of Radiating and Chemically Reacting Fluid Past An Accelerated Vertical Plate with Heat Sink

B. Prabhakar Reddy

Department of Mathematics, College of Natural & Mathematical Sciences, The University of Dodoma,
P. Box. No. 338, Dodoma, TANZANIA.

Department of Mathematics, Geethanjali College of Engineering & Technology,
Keesara (M), Medchal (Dist) - 501301, Telangana, INDIA.

Abstract: In this paper, the Soret effect on unsteady magneto-hydrodynamic (MHD) free convection flow of a viscous, incompressible, electrically conducting, radiating and chemically reacting fluid past an accelerated infinite vertical plate with variable temperature and mass diffusion under the influence of uniform transverse magnetic field, when the magnetic lines of force are fixed relative to the fluid ($\varepsilon = 0$) or to the moving plate ($\varepsilon = 1$) has been presented. The Rosseland approximation is used to describe the radiative heat flux in the energy equation for optically thick fluid. The system of partial differential equations governing the flow is transformed into non-dimensional form and then solved numerically by using Ritz finite element method. The effects of various physical parameters describing the flow transport on the fluid velocity, temperature and the concentration as well as the skin-friction coefficient, rate of heat and mass transfer presented through the graphs and tables and then discussed.

Keywords: MHD, magnetic field, heat absorption, chemical reaction, optically thick fluid.

I. Introduction

Free convection flow involving coupled heat and mass transfer occurs frequently in nature. It occurs not only due to temperature differences, but also due to concentration differences or a combination of these two. For example, in atmospheric flows there exist differences in the H_2O concentration. A few representative fields of interest in which combined heat and mass transfer plays an important role in designing of chemical processing equipment, distribution of temperature, formation and dispersion of fog and moisture over agriculture fields and groves of fruit trees, environmental pollution and crop damage due to freezing. The effects of radiation and chemical reaction on MHD boundary layer flow have become important in several industrial, scientific and engineering fields. There are many transport processes that are governed by the combined action of buoyancy forces due to both thermal and mass diffusion in the presence of chemical reaction. These processes are observed in nuclear reactor safety and combustion systems, solar collectors. Raptis and Singh [1] studied MHD free convection flow past an accelerated vertical plate by Laplace transform technique. Tokis [2] focused on unsteady magneto-hydrodynamic free convection flow near a moving plate in the presence of transverse magnetic field fixed relative to the fluid or to the moving plate. Unsteady MHD free convection flow past an impulsively started vertical plate with different boundary conditions was studied by [3] - [6]. MHD heat and mass transfer flow past an exponentially accelerated vertical plate through the porous medium was reported by [7] - [11]. MHD natural convection flow past an impulsively moving infinite vertical plate under the different conditions was studied by [12] - [16].

However, in the investigations mentioned above, the unsteady hydro-magnetic free convection flow past an infinite vertical plate subjected to a variable temperature and mass diffusion with Soret effect when the magnetic lines of force are fixed relative to the fluid or to the moving plate was not studied, even though this situation involves in many engineering and industrial applications. Hence, it is proposed to analyze the Soret effect on unsteady hydro-magnetic free convection flow of a radiating and chemically reacting fluid past an accelerated infinite vertical plate with heat sink under the influence of transverse magnetic field when the magnetic lines of force are being fixed relative to the fluid ($\varepsilon = 0$) or the moving plate ($\varepsilon = 1$). The governing system of dimensionless partial differential equations are solved numerically by applying the Ritz finite element method, which is more economical from computational point of view. The effects of physical parameters on the flow are presented through the graphs and tables and then discussed.

II. Mathematical Model

We consider an unsteady MHD free convection flow of a viscous incompressible, electrically conducting and chemically reacting fluid flow past an impulsively started infinite vertical plate with variable temperature and uniform mass diffusion in the presence of transverse applied magnetic field when the magnetic lines of force are fixed relative to the fluid or to the moving plate. The fluid is considered as a gray absorbing-emitting but non-scattering medium. We introduce the coordinate system with x' – axis along the plate in vertical upward direction and y' – axis is normal to the plate. A magnetic field of uniform strength B_0 is applied in the direction normal to the flow. The magnetic Reynolds number is small so that the induced magnetic field is negligible in comparison to the applied magnetic field. The plate is infinite in length, so all the field quantities become functions of the space coordinate y' and time t' . Initially ($t' \leq 0$), it is assumed that the plate and surrounding fluid are at the same temperature and concentration in a stationary condition for all the points in the entire flow region. Subsequently, at time $t' > 0$, the plate is given an impulsive motion with constant velocity $u' = u'_0 \exp(a'_0 t')$. Simultaneously, plate temperature is raised linearly with time t' and the concentration levels near the plate raised to C'_∞ . The influence of the density variation (ρ) with temperature and species concentration is considered only in the body force term. Under the above assumptions and invoking the Boussinesq's approximation, the governing equations of momentum, energy and concentration are derived as follows:

$$\frac{\partial u'}{\partial t'} = g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) + \nu \frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho} u' \quad (1)$$

$$\rho c_p \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r^*}{\partial y'} - Q'_0(T' - T'_\infty) \quad (2)$$

$$\frac{\partial C'}{\partial t'} = D \frac{\partial^2 C'}{\partial y'^2} + \frac{DK_T}{T_m} \frac{\partial^2 T'}{\partial y'^2} - k'_r(C' - C'_\infty) \quad (3)$$

where $u', T', C', \nu, g, \rho, T'_\infty, T'_w, C'_\infty, C'_w, c_p, k, D, \beta, \beta^*, Q'_0, k'_r, q_r^*, B_0$ and t' are fluid velocity, fluid temperature, fluid concentration, kinematic viscosity, acceleration due to gravity, fluid density, free stream temperature, surface temperature, free stream concentration, surface concentration, specific heat at constant pressure, thermal conductivity of the fluid, chemical molecular diffusivity, volumetric coefficient of thermal expansion, volumetric coefficient of concentration expansion, heat absorption coefficient, chemical reaction parameter, radiative heat flux, uniform magnetic field and time.

Equation (1) is valid, when the magnetic lines of force are fixed relative to the fluid. If the magnetic field is fixed relative to the plate, the momentum equation (1) is replaced by (Raptis and Singh [1], Tokis [2])

$$\frac{\partial u'}{\partial t'} = g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) + \nu \frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho} [u' - u_0 f(t')] \quad (4)$$

Note that the velocity $u_0 f(t')$ of the magnetic field B_0 in equation (4) appears because of the magnetic lines of force are fixed relative to the plate, which accelerate with velocity $u_0 f(t')$. Equations (1) and (4) combined as:

$$\frac{\partial u'}{\partial t'} = g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) + \nu \frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho} [u' - \varepsilon u_0 f(t')] \quad (5)$$

where $\varepsilon = 0$, if B_0 is fixed relative to the fluid
 $= 1$, if B_0 is fixed relative to the plate.

For an exponentially accelerated plate, $f(t') = \exp(a'_0 t')$, where a'_0 is the dimensionless accelerating parameter. The corresponding initial and boundary conditions are:

$$\begin{aligned} t' \leq 0; \quad u' = 0, T' = T'_\infty, C' = C'_\infty & \quad \forall y' \geq 0 \\ t' \geq 0; \quad u' = u \exp(a'_0 t'), T' = T_\infty + (T_w - T_\infty) A t', C' = C'_w & \quad \text{at } y' = 0 \\ u' \rightarrow 0, T' \rightarrow T'_\infty, C' \rightarrow C'_\infty & \quad \text{as } y' \rightarrow \infty \end{aligned} \quad (6)$$

where $A = \frac{u_0^2}{\nu}$. The radiative heat flux q_r^* under Rosseland approximation in case of optically thick fluid has the form:

$$q_r^* = -\frac{4\sigma^*}{3k^*} \frac{\partial T'^4}{\partial y'} \quad (7)$$

where σ^* and k^* are the Stefan-Boltzmann constant and the mean absorption coefficient, respectively. It is assumed that the temperature differences within the flow are sufficiently small such that the term T'^4 is expressed as the linear function of temperature. Therefore, expanding T'^4 about a free stream temperature T_∞' , using Taylor series expansion and neglecting higher order terms, one obtain

$$T'^4; T_\infty'^4 + 4T_\infty'^3(T' - T_\infty'); 4T_\infty'^3T' - 3T_\infty'^4$$

gives

$$q_r^* = -\frac{16\sigma^*T_\infty'^3}{3k^*} \frac{\partial T'}{\partial y'} \quad (8)$$

Using Eq. (8) into Eq. (3), we arrive at the energy equation

$$\rho c_p \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial y'^2} + \frac{16\sigma^*T_\infty'^3}{3k^*} \frac{\partial^2 T'}{\partial y'^2} - Q_0'(T' - T_\infty') \quad (9)$$

We introduce the following non-dimensional parameters and quantities.

$$u = \frac{u'}{u_0}, y = \frac{y'u_0}{\nu}, t = \frac{t'u_0^2}{\nu}, a_0 = \frac{\nu a_0'}{u_0^2}, \theta = \frac{T' - T_\infty'}{T_w' - T_\infty'}, \phi = \frac{C' - C_\infty'}{C_w' - C_\infty'}, P_r = \frac{\mu c_p}{k}, S_c = \frac{\nu}{D}, M = \frac{\sigma B_0^2 \nu}{\rho u_0^2},$$

$$\gamma = \frac{\nu k_r'}{u_0^2}, R = \frac{16\sigma^*T_\infty'^3}{3k^*k}, Q_H = \frac{Q_0'\nu}{\rho c_p}, F = \frac{P_r}{1+R}, L = FQ_H, G_r = \frac{g\beta\nu(T_w' - T_\infty')}{u_0^2}, G_m = \frac{g\beta^*\nu(C_w' - C_\infty')}{u_0^2}. \quad (10)$$

Substituting Eq. (10) into Eqs. (3), (5), (6) and (9) gives the governing equations in non-dimensional form:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + G_r\theta + G_m\phi - M[u - \varepsilon \exp(a_0 t)] \quad (11)$$

$$F \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} - L\theta \quad (12)$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{S_c} \frac{\partial^2 \phi}{\partial y^2} + S_r \left(\frac{\partial^2 \theta}{\partial y^2} \right) - \gamma\phi \quad (13)$$

The initial and boundary conditions in non-dimensional form are:

$$\begin{aligned} t \leq 0; \quad u = 0, \theta = 0, \phi = 0 \quad \forall \quad y \geq 0 \\ t > 0; \quad u = \exp(a_0 t), \theta = t, \phi = 1 \quad \text{at } y = 0 \\ u \rightarrow 0, \theta \rightarrow 0, \phi \rightarrow 0 \quad \text{as } y \rightarrow \infty \end{aligned} \quad (14)$$

III. Method of Solution

The dimensionless governing equations of the flow equations (11) to (13), subject to the initial and boundary conditions given in equation (14) are solved numerically by employing the Ritz finite element method. Details of the method are given in Reddy [17] and Bathe [18]. Finite element methods are widely used to solve boundary value problems, including many challenging heat transfer, biomechanics and metallurgical transport phenomenon problems over the past few years. The method entails the following steps.

- (1) Division of the whole domain into smaller elements of finite dimensions called finite elements.
- (2) Generation of element equations using variational formulation.
- (3) Assembly of element equations as derived in step (2).
- (4) Imposition of boundary conditions to the system of equations obtained in step (3).
- (5) Solution of the assembled algebraic equations.

The Gauss-Seidal iteration scheme is employed to solve the algebraic equations obtained in step (5). Numerical results for the velocity, temperature and the concentration fields are obtained by using C – program. The boundary condition $y \rightarrow \infty$ is approximated by $y_{\max} = 10$, which is sufficiently large for the velocity to approach convergence criterion. The computations are carried out until the steady state is reached. The steady state solution is assumed to have been reached when the absolute difference between any two time steps is less than 10^{-5} at all nodal points. To judge the convergence of the Ritz finite element method, computations are carried out by making small changes in space and time directions by running the same program, no significant change was observed in the values of u, θ and ϕ . Hence, we conclude that the Ritz finite element method is convergent and stable.

IV. Results and Discussion

In order to study the effects of various physical parameters on the flow, numerical computations have been carried out for the velocity, temperature and the concentration fields as well as the skin-friction coefficient, rate of heat and mass transfer. The obtained numerical results are presented through the graphs and tables. During the

numerical computation, the values of Prandtl number are chosen as $P_r = 0.71, 1.0, 7.0$ and 11.4 which corresponds to air, electrolytic solution, water and water at 40°C and the values of Schmidt number are taken as $S_c = 0.22, 0.60, 0.78$ and 1.0 , which corresponds to hydrogen, water-vapour, ammonia and methanol, respectively. The other physical parameters $G_r = 4.0, G_m = 4.0, R = 1.0, Q_H = 0.5, S_r = 1.0, \gamma = 0.5, M = 1.0, a_0 = 0.5$ and $t = 0.4$ are fixed unless specified in the figures and tables.

The effects of various physical parameters on the velocity distribution for an exponentially accelerated plate are presented in Figs.1-8, when the magnetic lines of force are fixed to the fluid ($\varepsilon = 0$) or to the moving plate ($\varepsilon = 1$), respectively. Figure 1 illustrates the effects of the radiation parameter R on the velocity profiles. It is seen that the fluid velocity increases with increasing values of the radiation parameter R due to the large values of R corresponds to an increased dominance of conduction over the radiation thereby increasing buoyancy force and thickness of the momentum boundary layer. The effects of chemical reaction parameter γ on the velocity profiles are shown in Fig.2. It is observed that increasing values of chemical reaction parameter γ leads to decrease in the fluid velocity. Figure 3 represents the effects of the heat absorption parameter Q_H on the velocity profiles. We found that increasing values of Q_H produces a decrease in the fluid velocity due to the presence of heat sink in the boundary layer absorbs energy, which in turn causes a decrease in the fluid temperature. This decrease in the temperature produces a decrease in the fluid flow due to the buoyancy effect, which couples the flow and thermal fields. The variation of the velocity profiles with increasing Soret number S_r is presented in Fig. 4. It can be seen that the fluid velocity increases with increasing values of Soret number. Figure 5 shows the effect of the magnetic parameter M on the velocity profiles. The velocity curves shows that an increase in the magnetic field parameter decreases the fluid velocity. It is due to the fact that application of the transverse magnetic field will result a Lorenz force similar to drag force, which tends to resist the flow fields and thus reducing the fluid velocity. Also, it is noticed that in case of moving plate the fluid velocity increases with increasing magnetic parameter due to increase in the momentum boundary layer thickness. Figure 6 sketched to show the effects of thermal Grashof number G_r on the velocity profiles. It is observed that fluid velocity increased in the boundary layer as G_r increased due to the buoyancy force enhances the fluid velocity and increases the boundary layer thickness. Here, the positive values of G_r corresponds to externally cooling of the plate. The effects of the mass Grashof number G_m on the velocity profiles are depicted in Fig.7. It is clearly seen that the effect of G_m on the fluid velocity is same as that of G_r . This result can be achieved by comparing Figs.6 and 7. The influence of exponential accelerated parameter a_0 on the velocity profiles is presented in Fig.8. It is found that an increase in the exponential accelerated parameter increases the fluid velocity. Figure 9 plotted to show the effect of t on the velocity profiles. It is observed that the fluid velocity increases with increasing values of t . This is due to an increase in the buoyancy force which causes an increase in the fluid velocity. Figure 10 depicts the effect of Prandtl number P_r on the temperature distribution. It is observed that the fluid temperature decreases in the boundary layer with increasing P_r . Physically, increasing values of P_r leads to decrease in the thermal boundary layer thickness and more uniform temperature distribution across the boundary layer. The effects of heat absorption parameter Q_H on the temperature distribution are shown in Fig.11. It is seen that there is a fall in the temperature as the heat absorption parameter increased. This is due to the fact that the presence of heat sink in the boundary layer absorbs energy, which in turn causes a decrease in the fluid temperature. Fig.12 shows the effect of radiation parameter R on the temperature distribution. It can be seen that the temperature θ is enhanced in the boundary layer as the radiation parameter R increased. Physically, large values of R correspond to an increased dominance of conduction over radiation thereby increasing the thickness of the thermal boundary layer. The effects of Schmidt number S_c on the concentration distribution ϕ are presented in Fig. 13. It is observed that an increase in the Schmidt number S_c leads to decreases the fluid concentration. This is due to increase of S_c leads to decrease of molecular diffusivity which results a decrease of concentration boundary layer thickness. Fig. 14 presents the effect of the Soret number S_r on the concentration distribution. The trend shows that there is a marked effect of increasing values of S_r on the concentration distribution in the boundary layer. It is noticed that the concentration of the fluid increases with increasing Soret number. Fig.15 depicts the effect of the chemical reaction parameter γ on the concentration profiles. It is found that increasing values of γ decreases the concentration of the species in the boundary layer due to the large values of γ reduce the solutal boundary layer thickness and increase the mass transfer.

The effects of physical parameters on the skin-friction coefficient (τ), Nusselt number (Nu) and the Sherwood number (Sh) are presented in tables 1-3, respectively. As seen from table 1 that an increase in R, S_r, t, G_r and G_m

tends to increase the skin-friction coefficient whereas an increase in Q_H, γ and a_o tends to decrease the skin-friction coefficient when the magnetic lines of force are being fixed relative to the fluid or to the moving plate. The skin-friction decreases as M increases in case of $\varepsilon = 0$ and the reverse effect is observed in case of $\varepsilon = 1$. It noticed from table 2 that the Nusselt number increases with increasing P_r and Q_H whereas it decreases with increasing R . It is seen from table 3 that an increase in S_c and γ tends to increase the Sherwood number whereas an increase in S_r decreases the Sherwood number.

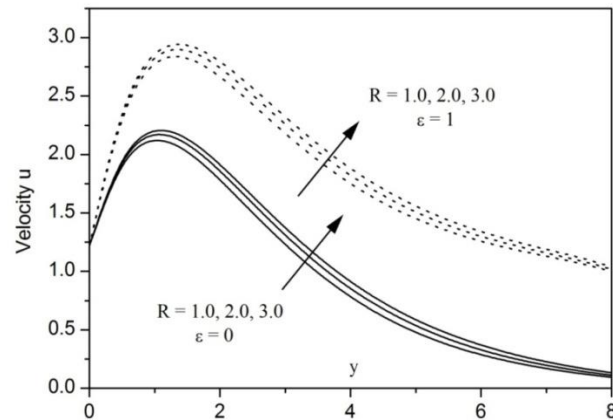


Fig.1: Effect of radiation parameter R on the velocity profiles.

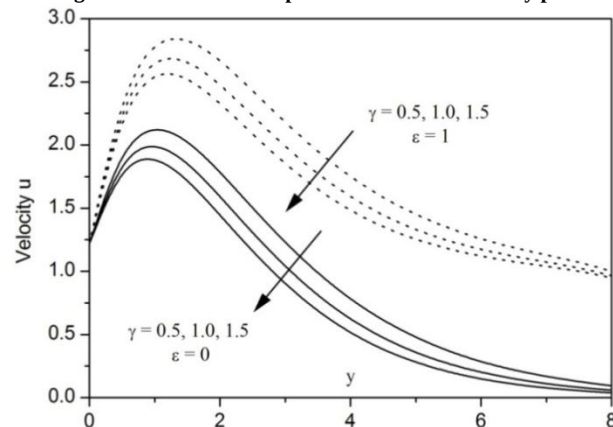


Fig.2: Effect of chemical reaction parameter γ on the velocity profiles.

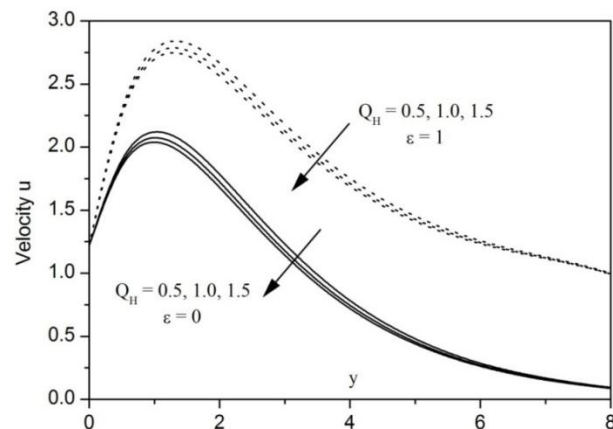


Fig.3: Effect of heat absorption parameter Q_H on the velocity profiles.

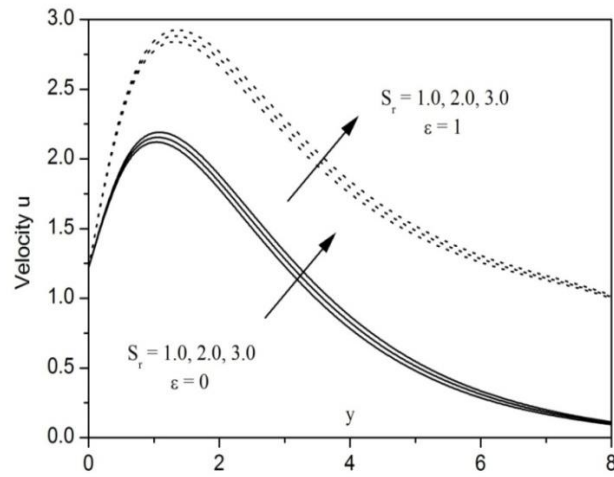


Fig.4: Effect of Soret number S_r on the velocity profiles.

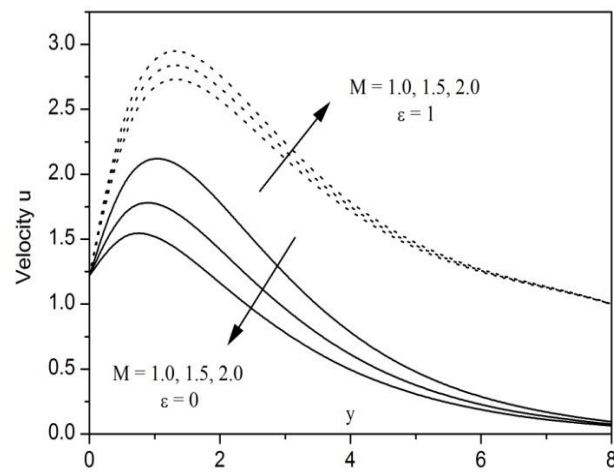


Fig.5: Effect of magnetic parameter M on the velocity profiles.

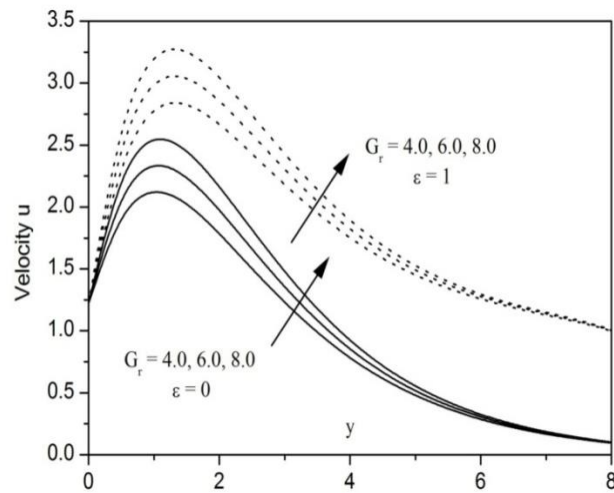


Fig.6: Effect of thermal Grashof number G_r on the velocity profiles.

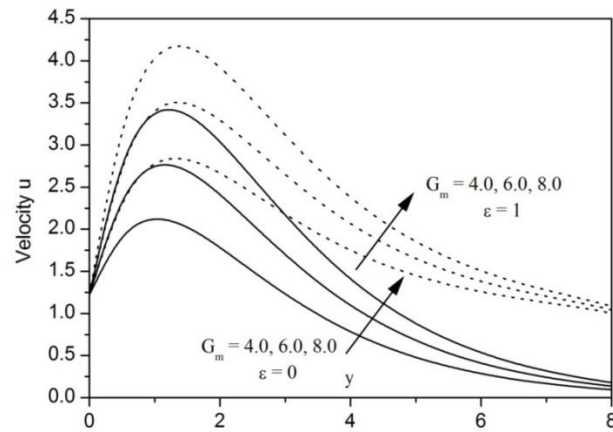


Fig.7: Effect of mass Grashof number G_m on the velocity profiles.

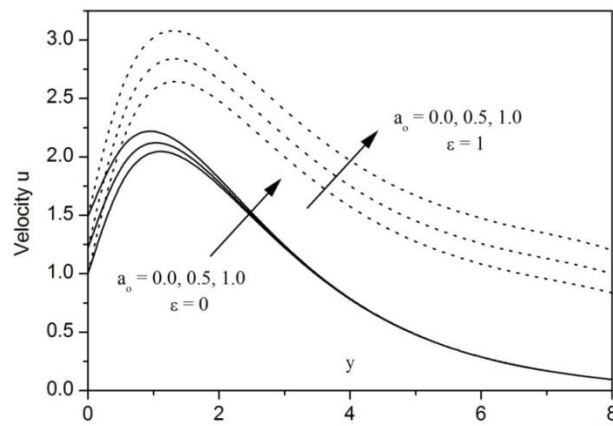


Fig.8: Effect of exponential acceleration parameter a_o on the velocity profiles.

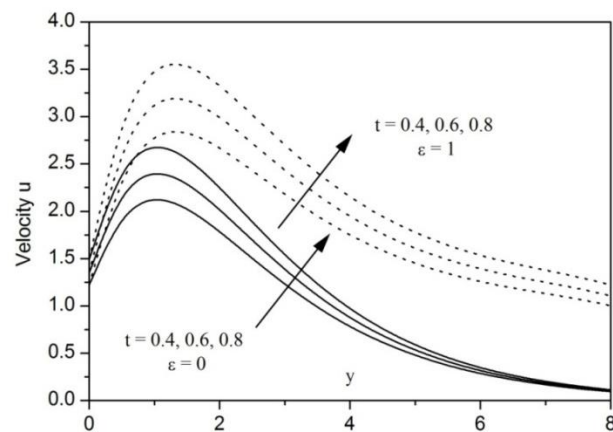


Fig.9: Effect of t on the velocity profiles.

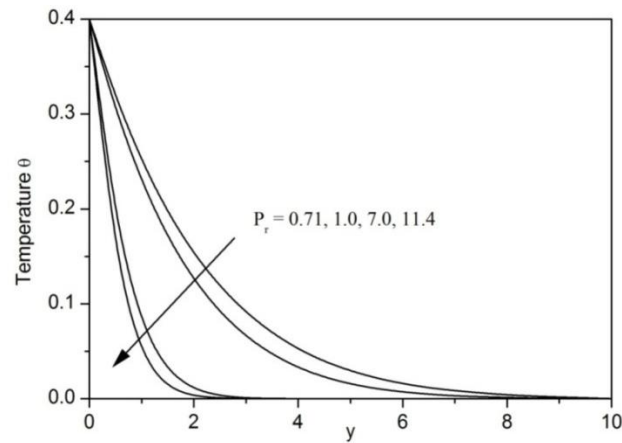


Fig.10: Effect of Prandtl number P_r on the temperature profiles.

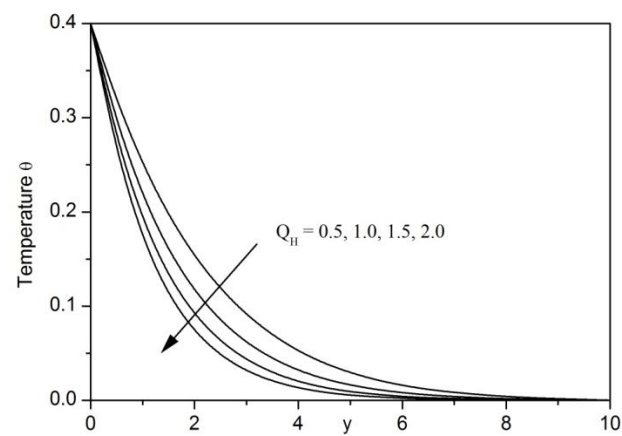


Fig.11: Effect of heat absorption parameter Q_H on the temperature profiles.

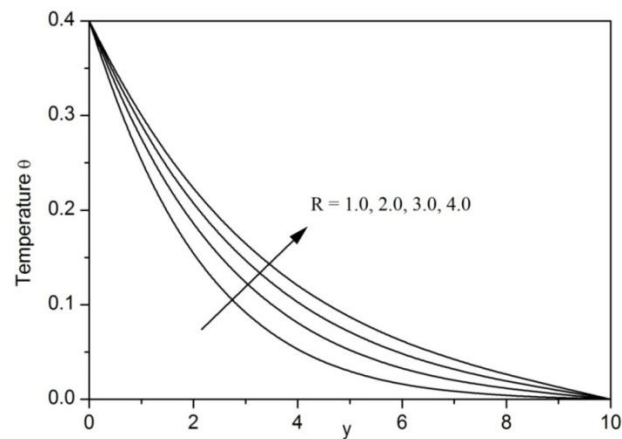


Fig.12: Effect of radiation parameter R on the temperature profiles.

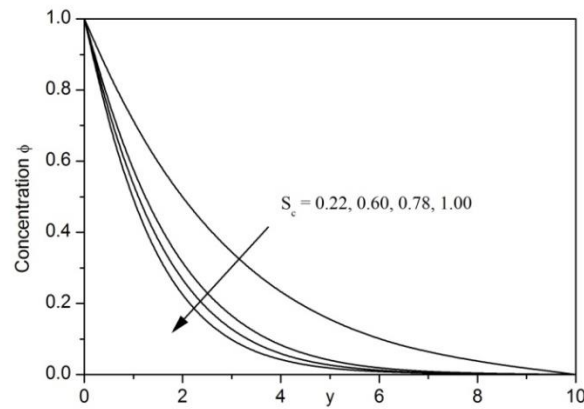


Fig.13: Effect of Schmidt number S_c on the concentration profiles.

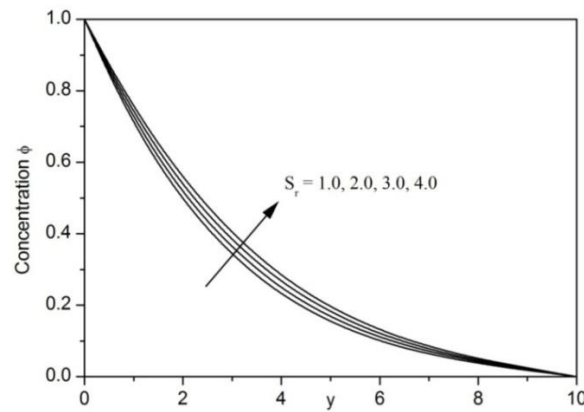


Fig.14: Effect of Soret number S_r on the concentration profiles.

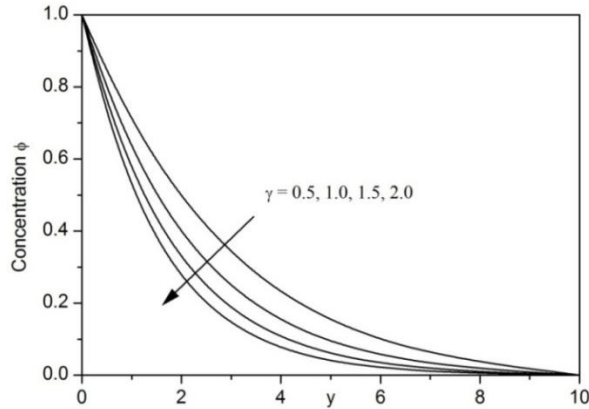


Fig.15: Effect of chemical reaction parameter γ on the concentration profiles.

Table 1: Effects of the physical parameters on the skin-friction coefficient (τ) when the magnetic lines of force are fixed relative to the fluid ($\varepsilon = 0$) or to the moving plate ($\varepsilon = 1$) and $P_r = 0.71, S_c = 0.22$.

R	Q_H	S_r	γ	M	a_o	t	G_r	G_m	$\tau(\varepsilon = 0)$	$\tau(\varepsilon = 1)$
1.0	0.5	1.0	0.5	1.0	0.5	0.4	4.0	4.0	1.548720	2.407890
2.0	0.5	1.0	0.5	1.0	0.5	0.4	4.0	4.0	1.603258	2.462428
1.0	1.0	1.0	0.5	1.0	0.5	0.4	4.0	4.0	1.494806	2.353976
1.0	0.5	2.0	0.5	1.0	0.5	0.4	4.0	4.0	1.586974	2.446142
1.0	0.5	1.0	1.0	1.0	0.5	0.4	4.0	4.0	1.396962	2.256132
1.0	0.5	1.0	0.5	1.5	0.5	0.4	4.0	4.0	1.068878	2.464241
1.0	0.5	1.0	0.5	1.0	1.0	0.4	4.0	4.0	1.629836	2.579226
1.0	0.5	1.0	0.5	1.0	0.5	0.6	4.0	4.0	1.794354	2.743882
1.0	0.5	1.0	0.5	1.0	0.5	0.4	6.0	4.0	1.879202	2.738370
1.0	0.5	1.0	0.5	1.0	0.5	0.4	4.0	6.0	2.486914	3.346082

Table 2: Effects of P_r , R and Q_H on the Nusselt number (Nu).

P_r	R	Q_H	Nu
0.71	1.0	0.5	0.164834
7.00	1.0	0.5	0.431512
0.71	2.0	0.5	0.136676
0.71	1.0	1.0	0.210358

Table 2: Effects of S_c , S_r and γ on the Sherwood number (Sh).

S_c	S_r	γ	Sh
0.22	1.0	0.5	0.311734
0.60	1.0	0.5	0.484824
0.22	2.0	0.5	0.293240
0.22	1.0	1.0	0.409728

V. Conclusions

We have examined the governing equations of the flow for the Soret effect on unsteady MHD free convection flow of a radiating and chemically reacting fluid past an accelerated infinite vertical plate with heat sink under the influence of transverse magnetic field, when the magnetic lines of force fixed relative to the fluid ($\varepsilon = 0$) or to the moving plate ($\varepsilon = 1$). The leading governing system of partial differential equations is solved numerically by using the Ritz finite element method. It has been found that an increase in R , S_r , a_o , t , G_r and G_m tends to increase the fluid velocity whereas it decreases with increase in γ and Q_H when the magnetic lines of force are fixed relative to the fluid or to the moving plate. An increase M decelerates the fluid flow in case of the magnetic lines of force are fixed relative to the fluid and opposite effect is observed in case of magnetic lines of force fixed relative to the moving plate. Also, we observe that The magnetic lines of force are fixed relative to the fluid ($\varepsilon = 0$), the values of the fluid velocity are lower than in the case of the magnetic lines of force are fixed relative to the moving plate ($\varepsilon = 1$).

VI. References

- [1] A. Raptis and A. K. Singh, "MHD free convection flow past an accelerated vertical plate" Comm. Heat and Mass Transfer, vol.10, (1982), pp.313 – 321.
- [2] J. N. Tokis, "A class of exact solutions of the unsteady magneto-hydrodynamic free convection flows", Astrophysics Space Science, vol.112, (1985), pp. 413-122.
- [3] N. C. Sacheti, P. Chandraan and A. K. Singh, "Exact solution for unsteady MHD free convection flow on an impulsively started vertical plate with constant heat flux", Int. Comm. Heat Mass Transfer, vol.21, No. 1, (1994), pp.131-142.
- [4] R. Muthucumaraswamy, P. Ganesan and V. M. Soundalgekar, "Heat and mass transfer effects on flow past an impulsively starts vertical plate", Acta Mechanica, vol.146, No.1-2, (2001), pp.1 – 8.
- [5] S. Suneetha, N. Bhaskar Reddy and V. Ramachandra Prasad, "Thermal radiation effects on MHD free convection flow past an impulsively started vertical plate with variable surface temperature and concentration", J. Naval Archit. Marine Eng, vol.5, No.2, (2008), pp.57 – 70.
- [6] R. Swetha, J. Prakash, G. Viswanatha Reddy and S. V. K. Varma, "Effects of thermal radiation and radiation absorption on flow past an impulsively started infinite vertical plate with Newtonian heating and chemical reaction", Open Journal of Fluid Dynamics, vol.5, No.4, (2015), pp.364-379.
- [7] R. Muthucumaraswamy, K. E. Sathappan and R. Natarajan, "Mass transfer effects on exponentially accelerated isothermal vertical plate", Int. J. Appl. Math and Mech, vol.4, No.6, (2004), pp.19 – 25.
- [8] V. Rajesh and S. V. K. Varma, "Radiation and mass transfer effects on MHD free convection flow past an exponentially accelerated moving plate with variable temperature", ARPN, J. Eng. Appl. Sci, vol.4, No.6, (2009), pp.20 – 26.
- [9] V. Rajesh and S. V. K. Varma, "Heat source effects on MHD flow past an exponentially accelerated vertical plate with variable temperature through a porous medium", Int. J. Appl. Math and Mech., vol.6, No.2, (2010), pp.68-78.
- [10] M. Narahari and L. Debnath, "Unsteady magneto-hydrodynamic free convection flow past an accelerated vertical plate with constant heat flux and heat generation/absorption", ZAMM, Z. Angew. Math. Mech, vol.93, No.1, (2013), pp. 38 – 49.
- [11] P. M. Kishore, N. V. R. V. Prasad Rao, S. V. K. Vrama and S. Venkataramana, "The effects of radiation and chemical reaction on unsteady MHD free convection flow of viscous fluid past an accelerated vertical plate", Int. J. Physical and Mathematical Sci, vol.4, No.1, (2013), pp.300-317.
- [12] K. Das, "Exact solution of MHD free convection flow and mass transfer near a moving vertical plate in the presence of thermal radiation", African J. Math. Phys, vol.8, (2010), pp.29-41.
- [13] K. Das and S. Jana, "Heat and mass transfer effects on unsteady MHD free convection flow near a moving vertical plate in porous medium", Bull. Soc. Math. Banja Luka, vol.17, No.10, (2010), pp.15 – 32.
- [14] G. S. Seth, MD. Ansari and R. Nandkeolyar, "MHD natural convection flow with radiative heat transfer past an impulsively moving plate with ramped wall temperature", Heat Mass Transfer, vol.47, (2011), pp. 551-561.
- [15] N. Ghara, S. Das, S. L. Maji and R. N. Jana, "Effect of radiation on MHD free convection flow past an impulsively moving vertical plate with ramped wall temperature", Am. J. Sci. Ind. Res, vol.3, No.6, (2012), pp. 376-386.
- [16] G. S. Seth, R. Nandkeolyar and MD. Ansari, "Effects of thermal radiation and rotation on unsteady hydro-magnetic free convection flow past an impulsively moving vertical plate with ramped temperature in a porous medium", J. Appl. Fluid Mech, vol.6, (2013), pp.27 – 38.
- [17] J. N. Reddy, "An introduction to the finite element method", MacGraw-Hill, New York, (1985).
- [18] K. J. Bathe, "Finite element procedures", Prentice-Hall, New Jersey, (1996).