Effect of thermal diffusion and chemical reaction on MHD free convective flow past an infinite isothermal vertical plate with heat source

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Abstract. An attempt has been made to study the heat and mass transfer effect on an MHD free convection flow of an electrically conducting viscous fluid past over a moving infinite isothermal vertical plate subject to transverse magnetic field in presence of Soret effect, chemical reaction, heat source and thermal radiation. Exact solutions for velocity field, temperature profile and concentration distribution are obtained using Laplace transformation technique in closed form. Expressions for skin friction, rate of heat transfer and rate of mass transfer are also derived. The effects of different physical parameters on the various fields are studied graphically.

Keywords: heat and mass transfer, thermal radiation, chemical reaction, thermal diffusion and heat source.

Introduction

The phenomenon concerning heat and mass transfer with MHD flow is important due to its numerous applications in science and technology, industrial processes and devices namely MHD accelerator, casting and levitation atmospheric winds etc. Study of thermal radiation effects on MHD flow in fluid mechanics is very important to the engineers showing meaning to this field in our economic growth. Thermal radiation and its effects on MHD flow are major input of researchers in recent past. Prasad et al. (2012) examined the thermal radiation effects on magneto hydrodynamic free convection heat and mass transfer from a sphere in a variable porosity regime. Raju et al. (2014) carried out a analytical study

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of MHD free convection, dissipative boundary layer flow past a porous vertical surface in presence of thermal radiation, chemical reaction and constant suction. Radiation and mass transfer effects on MHD oscillatory flow in a channel filled with porous medium in presence of chemical reaction was investigated by Ibrahim et al. (2015). Bhuvaneswari et al. (2010) reported the exact analysis of radiation convection flow with heat and mass transfer over an inclined plate in a porous medium. Several researchers investigated MHD flow through a fluid saturated porous and non-porous medium near vertical plate considering different aspects of the problem. Relevant studies are due to Raptis et al. (2004), Raptis and Kafoussias (1982), Geindrean and Auriault (2002), Chen (2009), Seth et al.(2011, 2014, 2015, 2017) etc.

It is well known that, the driving potential for the phenomena of transport of mass is not alone concentration gradients, but high temperature gradient also. Mass transfer created by temperature gradient is called as thermal diffusion effect i.e. Soret effect. The Soret effect has been utilized for isotope separation and in mixture between gases of very light molecular weight and medium molecular weight. The importance of this effect in convection transport has been reported by Eckert and Darke (1972). The study of heat source effects on heat transfer is very important because of effects are crucial in controlling the heat transfer and in cooling processes. Turkyilmazoglu and Pop (2012) studied Soret and heat source effects on the unsteady radiative MHD free convection flow from an impulsively started infinite vertical plate. Ahmed (2012b) investigated the effects of heat and mass transfer in Hartmann flow with Soret effect in presence of a constant heat source. Singh (2001) discussed MHD free convection and mass transfer flow with heat source and thermal diffusion. Ibrahim and Suneetha (2015) analyzed chemical reaction and Soret effects on unsteady MHD flow of a viscoelastic fluid past an impulsively started infinite vertical plate with heat Source. Ahmed (2012a) discussed the Soret and radiation effects on transient MHD free convection from an impulsively started infinite vertical plate. Zimmerman et al. (1992) studied convection in two component system with Soret effect. Raptis (1982) considered free convection and mass transfer effects on the oscillatory flow past an infinite moving vertical isothermal plate with constant suction and heat source. Krishnendu Bhattacharyya (2011) investigated the effects of radiation and heat source/sink on unsteady MHD boundary layer flow and heat transfer over a stretching sheet with suction/injection. Chamkha (2000) studied thermal radiation and buoyancy effects on hydromagnetic flow over an accelerating permeable surface with heat source or sink.

The study of heat and mass transfer with chemical reaction is of great practical importance for engineers and scientists because of its almost universal occurrence in many branches of science and engineering. In most of chemical engineering processes chemical reaction occurs between a foreign mass on the fluid. It can be classified as either heterogeneous or homogeneous processes. Possible applications of this type of flow can be found in many industries like power and chemical process industries. Astarita (1967) discussed the mass transfer with chemical reaction. Effects of chemical reaction on a moving isothermal surface with suction were studied by Muthucumaraswamy(2002). Raju et al. (2013) presented unsteady MHD free convection and chemically reactive flow past an infinite vertical porous plate. Chemically reacting MHD boundary layer flow of heat and mass transfer over a moving vertical plate with suction was investigated by Ibrahim and Makinde (2010).

The objective of the present problem is to examine the effect of thermal diffusion and chemical reaction on MHD free convection flow past an infinite isothermal vertical plate with heat source. This present work is a generalization of the work done by Muthucumaraswamy and Sivkumar(2016) to consider the effect of heat source on the flow characteristics.

Mathematical analysis

Consider two dimensional unsteady free convection flow of a viscous incompressible fluid past an infinite isothermal moving vertical plate in presence of thermal diffusion, thermal radiation, chemical reaction and heat source. We take x' axis along the plate in the direction of fluid flow and y' -axis normal to it. A uniform transverse magnetic field of strength B_0 is assumed to be applied in the positive y' direction namely normal to the plate and chemical reaction is also taking place in the flow.

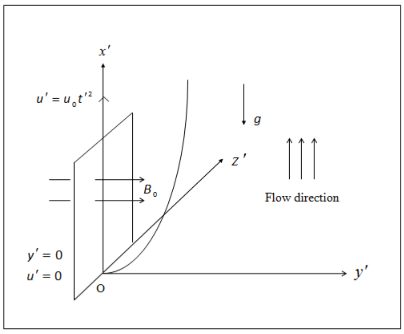

Figure 1: Physical configuration of the problem.

At $t' \leq 0$, the plate and fluid are at rest and at the uniform temperature T'_∞ and uniform species concentration C'_∞. At $t' > 0$, the plate begins to move with a velocity $u' = u_0 t'^2$ against the gravitational force g .In this analysis, the magnetic Reynolds number is taken to be small so that induced magnetic field can be neglected. The fluid is gray, absorbing-emitting radiant but a non scattering medium. Chemical reaction is assumed to be homogeneous and of first order. Under the Boussinesq approximation Equatoins governing the conservation of mass, momentum, energy and concentration can be written as

$$\frac{\partial v'}{\partial y'} = 0, \tag{1}$$

$$\frac{\partial u'}{\partial t'} = g\beta(T' - T'_\infty) + g\beta_c(C' - C'_\infty) + \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_o^2}{\rho}u', \tag{2}$$

$$\rho C_p\frac{\partial T'}{\partial t'} = \kappa\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} - Q'(T' - T'_\infty), \tag{3}$$

$$\frac{\partial C'}{\partial t'} = D_M\frac{\partial^2 C'}{\partial y'^2} - K_1(C' - C'_\infty) + D_T\frac{\partial^2 T'}{\partial y'^2} \tag{4}$$

Initial and boundary conditions are

$$\begin{aligned} &u' = 0, \quad T' = T'_\infty, \quad C' = C'_\infty \quad \text{for all } \; y',\, t' \le 0 \\ &t' > 0, \quad u' = u_0 t'^2, \quad T' = T'_w, \quad C' = C'_w \;\text{ at } y' = 0 \\ &u' \to 0, \quad T' \to T'_\infty, \quad C' \to C'_\infty \quad as\ y' \to \infty \end{aligned} \tag{5}$$

The local radiant for the case of an optically thick gray gas is expressed by

$$\frac{\partial q_r}{\partial y'} = -4a^*\sigma^*\left(T'^4_\infty - T'^4\right) \tag{6}$$

We assume that the temperature differences within the flow are sufficiently small and on using Taylors Series to expand T'^4 about T'_∞ and neglecting higher order terms, we derive

$$T'^4 = 4T'^3_\infty T' - 3T'^4_\infty \tag{7}$$

By using (6) and (7); equation (3) reduces to

$$\rho C_p\frac{\partial T'}{\partial t'} = \kappa\frac{\partial^2 T'}{\partial y'^2} + 16a^*\sigma^* T'^3_\infty\left(T'_\infty - T'\right) - Q'(T' - T'_\infty) \tag{8}$$

We introduce the following non-dimensional quantities:

$$\begin{aligned} &u = u'\left(\frac{1}{u_0\nu^2}\right)^{\frac{1}{5}},\ t = \left(\frac{u_0^2}{\nu}\right)^{\frac{1}{5}} t',\ y = y'\left(\frac{u_0}{\nu^3}\right)^{\frac{1}{5}}, \\ &Pr = \frac{\mu C_p}{\kappa},\ Sc = \frac{\nu}{D_M},\ K = K_1\left(\frac{\nu}{u_0^2}\right)^{\frac{1}{5}} \\ &Gr = \frac{g\beta\left(T'_w - T'_\infty\right)}{\left(\nu u_0^3\right)^{\frac{1}{5}}},\quad Gm = \frac{g\beta_c\left(C'_w - C'_\infty\right)}{\left(\nu u_0^3\right)^{\frac{1}{5}}}, \end{aligned} \tag{9}$$

$$M = \frac{\sigma B_0^2}{\rho}\left(\frac{\nu}{u_0^2}\right)^{\frac{1}{5}}, \quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}$$

$$\phi = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \qquad N = \left(\frac{\nu^3}{u_0}\right)^{\frac{2}{3}} \frac{16a^*\sigma^* T'^3_\infty}{\kappa},$$

$$Sr = \frac{D_T\left(T'_w - T'_\infty\right)}{\nu\left(C'_w - C'_\infty\right)}, \qquad Q = \frac{Q'\nu^{\frac{1}{5}}}{\rho C_p u_0^{2/5}}.$$

The non-dimensional form of the governing equations (2), (3) and (4) are as follows:

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

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} - \frac{1}{Pr}N\theta - Q\theta, \tag{11}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} - K\phi + Sr\frac{\partial^2 \theta}{\partial y^2}. \tag{12}$$

Corresponding initial and boundary conditions in dimensionless forms become

$$\begin{aligned} &u = 0, \quad \theta = 0, \quad \phi = 0 \qquad \text{for all } y,\ t \le 0,\\ &t > 0, \quad u = t^2,\ \theta = 1,\ \phi = 1 \quad \text{at } y = 0,\\ &u \to 0,\ \theta \to 0,\ \phi \to 0 \qquad \text{as } y \to 0. \end{aligned} \tag{13}$$

Taking Laplace transform of equations (10), (11), (12) and (13) the equations are transformed into 2nd order ordinary differential equation. These equations are further inverted and solved subject to the transformed boundary condition. So that the following solutions for ϕ, $\theta$and u are obtained

$$\theta = f_1\left(Pr, y, A_2, t\right), \tag{14}$$

$$\begin{aligned} \phi = {} & (1 + A_4)\, f_1\left(Sc, y, K, t\right) + A_5\, e^{A_3\, t} f_1\left(Sc, y, A_3, t\right)\\ & - A_4\, f_1\left(Pr, y, A_2, t\right) - A_5\, e^{A_3\, t}\, f_1\left(Pr, y, A_{31}, t\right), \end{aligned} \tag{15}$$

$$\begin{aligned} u = {} & \left\{\left(\frac{y^2 + 4Mt^2}{8M}\right) f_2\left(M, y, t\right) + \left(\frac{y\left(1 - 4Mt\right)}{16M^{3/2}}\right)\, f_3\left(M, y, t\right)\right.\\ & \left. - \left(\frac{y\sqrt{t}}{2M\sqrt{\pi}}\right)\, e^{-\left(\frac{y^2}{4t} + Mt\right)}\right\}\\ & +\ A_{19}\, e^{A_{11} t}\, f_1\left(1, y, A_{25}, t\right)\ + A_{20} f_1\left(1, y, M, t\right)\\ & +\ A_{21}\, e^{A_{12} t} f_1\left(1, y, A_{26}, t\right) + A_{22} e^{A_3 t} f_1\left(1, y, A_{27}, t\right)\\ & +\ A_{23} e^{A_3 t} f_1\left(Pr, y, A_{28}, t\right) - A_{14} f_1\left(Pr, y, A_2, t\right)\\ & + A_{15} f_1\left(Sc, y, K, t\right) + A_{24} e^{A_{11} t} f_1\left(Sc, y, A_{29}, t\right)\\ & - A_{16} e^{A_3 t} f_1\left(Sc, y, A_{30}, t\right)\\ & + A_{18} e^{A_3 t} f_1\left(Pr, y, A_{31}, t\right), \end{aligned} \tag{16}$$

where

$$f_1(x,y,z,t)=\frac{1}{2}\left[e^{y\sqrt{xz}}erfc\left(\frac{y}{2}\sqrt{\frac{x}{t}}+\sqrt{zt}\right)+e^{-y\sqrt{xz}}erfc\left(\frac{y}{2}\sqrt{\frac{x}{t}}-\sqrt{zt}\right)\right],$$
$$f_2(z,y,t)=\left[e^{y\sqrt{z}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{zt}\right)+e^{-y\sqrt{z}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{zt}\right)\right],$$
$$f_3(z,y,t)=\left[e^{-y\sqrt{z}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{zt}\right)-e^{-y\sqrt{z}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{zt}\right)\right].$$

Skin friction

The expression for the skin friction or shear stress at the plate is given by

$$\begin{aligned}\tau &= \left.\frac{\partial u}{\partial y}\right]_{y=0}\\ &= t^2 f_6(M,t)+f_4(M,t)-f_5(M,t)+A_{19}e^{A_{11}t}f_6(A_{25},t)+A_{20}f_6(M,t)\\ &+A_{21}e^{-A_{12}t}f_6(A_{26},t)+A_{22}e^{A_3t}f_6(A_{27},t)+A_{23}e^{A_{11}t}f_6(Pr,A_{28},t)\\ &-A_{14}f_6(Pr,A_2,t)+A_{15}f_6(Sc,K,t)+A_{24}e^{A_{12}t}f_6(Sc,A_{29},t)\\ &-A_{16}e^{A_3t}f_6(Sc,A_{30},t)+A_{18}e^{A_3t}f_6(Pr,A_{31},t),\end{aligned}\tag{17}$$

where

$$f_4(M,t)=\left(\frac{1-4Mt}{16M^{3/2}}\right)\left[erfc\left(-\sqrt{Mt}\right)-erfc\left(\sqrt{Mt}\right)\right],$$
$$f_5(M,t)=\frac{e^{-Mt}}{2M}\left(\sqrt{\frac{t}{\pi}}\right),$$
$$f_6(x,z,t)=\frac{1}{2}\left[\sqrt{xz}\left\{erfc\left(\sqrt{zt}\right)-erfc\left(-\sqrt{zt}\right)\right\}-\frac{2\sqrt{x}e^{-zt}}{\sqrt{\pi t}}\right].$$

Nusselt number

Expression for the rate of heat transfer at the plate in terms of Nu is given by

$$\begin{aligned}Nu &= -\left.\frac{\partial\theta}{\partial y}\right]_{y=0}\\ &= -f_6(Pr,A_2,t)\end{aligned}\tag{18}$$

Sherwood number

Expression for the rate of mass transfer at the plate in terms of Sh is given by

$$\begin{aligned}Sh &= \left.\frac{\partial\phi}{\partial y}\right]_{y=0}\\ &= (1+A_4)f_6(Sc,K,t)+A_5e^{A_3t}f_6(Sc,A_{30},t)\\ &-A_4f_6(Pr,A_2,t)-A_5e^{A_3t}f_6(Pr,A_{31},t)\end{aligned}\tag{19}$$

Results and discussion

In order to get a clear insight of the physical problem, numerical computations have been carried out for various values of different parameters such as Prandtl number (Pr), thermal Grashof number (Gr), mass Grashof number (Gm), magnetic parameter (M), Soret number (Sr), thermal radiation (N), heat source (Q) and chemical reaction (K). For illustrations of the results, numerical values are plotted in the figures $(2-18)$.

Figures $(2-9)$ demonstrate the pattern of the velocity, temperature and concentration distributions obtained from the analytical solutions of the problem.The effects of Soret number on the velocity field and concentration profile are shown in Figures 2 and 3. These figures exhibit that the velocity and concentration of the fluid increase with increase in Soret number. Soret number is associated with the ratio of temperature difference and concentration gradient. Hence the greater Soret number stands for larger temperature difference and precipitous gradient. Thus the fluid velocity rises due to greater thermal diffusion factor.

Figures $4, 5$ and 6 illustrate the dimensionless velocity, temperature and concentration distribution for different values of heat source parameter. It is observed that the velocity and temperature profiles decrease as heat source parameter increases in contrast the concentration profile raise for increasing values of heat Source. Figure 7 reveals the effects of the magnetic field parameter (M) on velocity field. From this figure it is observed that the velocity of fluid decreases for increasing of magnetic parameter (M). It is due to the fact that the presence of transverse magnetic field produces a resistive force called Lorentz force, which leads to slow down the motion of fluid.Figure 8 and 9 exhibit the velocity field and concentration distribution against y for different values of chemical reaction parameter. From these two figures we observe that as chemical reaction parameter increases velocity and concentration decrease. It is noticed that the fluid motion and concentration increases quickly up to some thin layer of the fluid adjacent to the plate and then decreases asymptotically as we move far away from the plate.

The influence of radiation parameter, Soret number and heat Source effects on skin friction with respect to time t is shown graphically in Figures $10, 11$ and 12 respectively. It is observed that the viscous drag increases due to an increase in either of the Soret number, or heat source or the thermal radiation effect. Thus the effects thermal-diffusion, thermal radiation and heat source are effective mechanism in controlling the viscous drag at the plate to a considerable extent. The magnitude of the heat transfer coefficient for various values of thermal radiation (N) and heat source (Q) are given in Figures 13 and 14. It is observed that the rate of heat transfer coefficient in case of air decreases whenever there is an increase in either thermal radiation (N) or heat source (Q). That is to say that the effect of radiation or heat source causes the rate of heat transfer from the plate to fall to some extent.The rate of mass transfer coefficient for various values of thermal-diffusion and heat source is given in Figures 15 and 16. It is noticed that the rate of mass transfer at the plate increases when either there is an increase in Soret number (Sr) or there is an increase in the heat source parameter (Q).In other words the rate of mass transfer from the plate to the fluid gets enhance due to Soret number as well as heat source effect.

In the absence of thermal diffusion and heat source (i.e. $Sr = 0$, $Q = 0$), the results obtained in the present work are in good agreement with that obtained by Muthucumaraswamy and Sivkumar (2016), Figure 17 shows the effect of magnetic field parameter M (when $Sr = 0$ and $Q = 0$) on the velocity profile and the outcome is compared with Figure 18 (Figure 3 of the work Muthucumaraswamy and Sivkumar (2016)). It is seen that both the figure exactly coincide, depicting similar result that the velocity decreases with the application of transverse magnetic field.

Conclusion

Our theoretical investigation can be summarized to the following conclusions:

- The velocity of fluid decreases with increasing values of heat Source but reverese trend is shown in case of concentration profile.
- Increase in Soret number results and enhancement in velocity and concentration of the fluid.
- With increasing values of heat Source parameter the temperature profile falls decrease.
- Application of transverse magnetic field causes the velocity of the fluid to reduce comprehensively.
- The viscous drag at the plate is enhanced in magnitude with increase in thermal radiation, Soret number and heat Source.
- The rate of heat transfer decreases with the increasing values of thermal radiation and heat source parameter.
- The rate of mass transfer contributes to increase with the increasing values of thermal diffusion and heat Source.

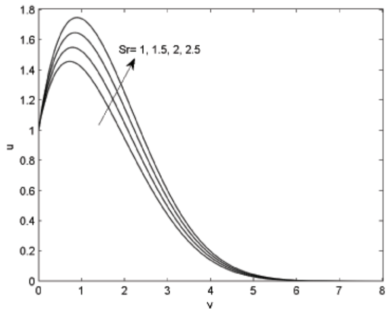

Fig. 2 Velocity versus y for $Pr = .71, Gr = 3, Gm = 3, Sc = .60, N = 1, M = 1, Q = .2, K = .50, t = 1$

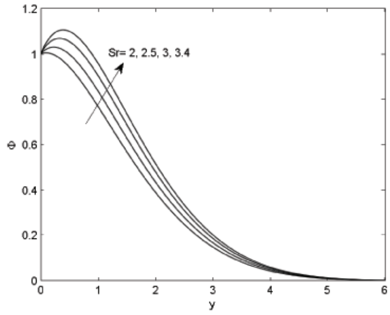

Fig. 3 Concentration versus y for $Pr = .71, Sc = .60, N = 1, Q = .2, K = .50, t = 1$

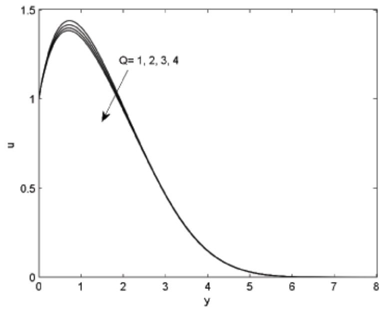

Fig. 4 Velocity versus y for $Pr = .71, Gr = 3, Gm = 3, Sc = .60, Sr = 1, N = 1, M = 1, K = .50, t = 1$

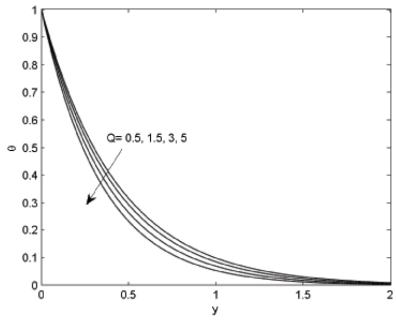

Fig. 5 Temperature versus y for $Pr = .71, N = 5, t = .7$

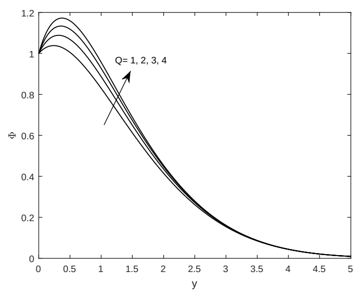

Fig. 6 Concentration versus y for $Pr = .71, Sc = .60, Sr = 2, N = 1, K = .50, t = 1$

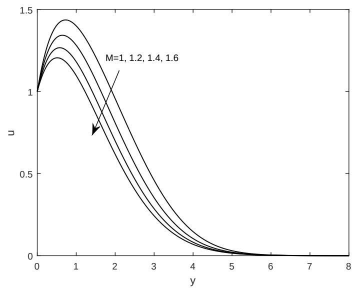

Fig. 7 Velocity versus y for $Pr = .71, Gr = 3, Gm = 3, Sc = .60, Sr = 1, N = 1, Q = 1, K = .50, t = 1$

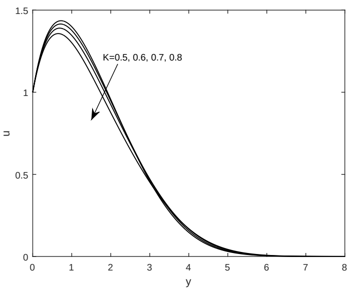

Fig. 8 Velocity versus y for $Pr = .71, Gr = 3, Gm = 3, Sc = .60, Sr = 1, N = 1, M = 1, Q = 1, t = 1$

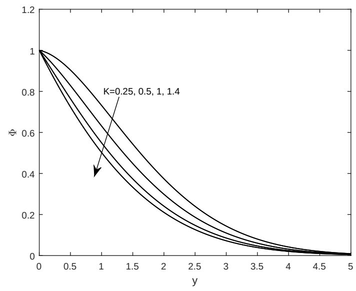

Fig. 9 Concentration versus y for $Pr = .71, Sc = .60, Sr = 1, N = 1, Q = .2, t = 1$

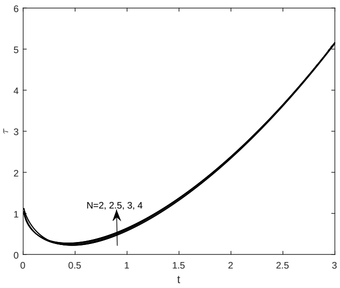

Fig. 10 Skin friction versus t for $Pr = .71, Gr = 2, Gm = 2, Sc = .60, Sr = 2, Q = .5, K = 1, M = 1$

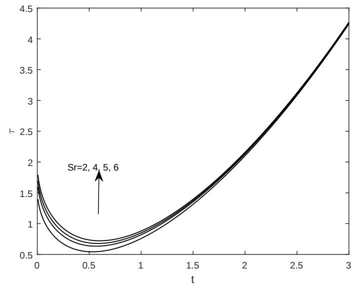

Fig. 11 Skin friction versus t for $Pr = .71, Gr = 2, Gm = 2, Sc = .60, N = .25, Q = .5, K = 1, M = 1$

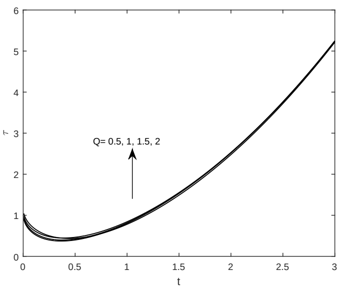

Fig. 12 Skin friction versus t for $Pr = .71, Gr = 2, Gm = 2, Sc = .60, N = .25, Q = .5, K = 1, M = 1$

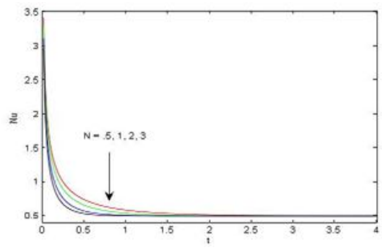

Fig. 13 Nusselt number versus t for $Pr = .71, Q = .5$

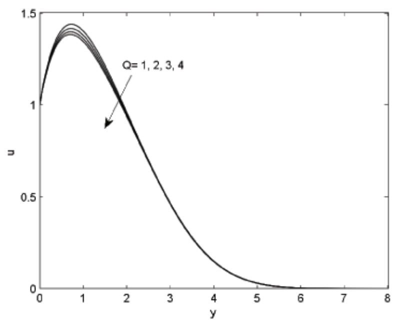

Fig. 14 Nusselt number versus t for $Pr = .71, N = .5$

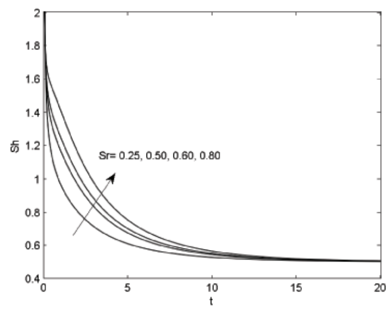

Fig. 15 Sherwood number versus t for $Pr = .71, Sc = .60, N = .50, Q = .5, K = .2$

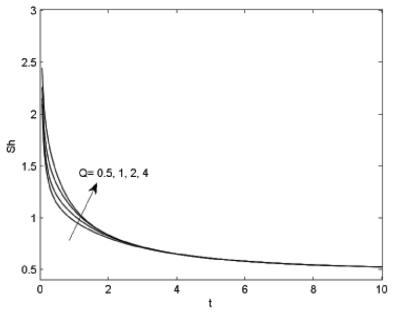

Fig. 16 Sherwood number versus t for $Pr = .71, Sc = .60, N = .50, Sr = .5, K = .2$

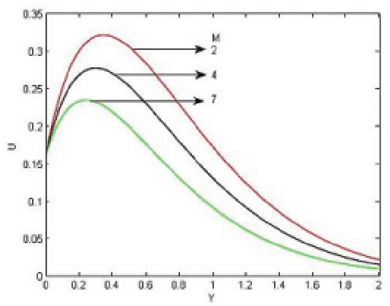

Fig. 17 Velocity versus y for $Pr = .71, Gr = 3, Gm = 3, Sc = .60, Sr = 0, N = 10, Q = 1, K = 10, t = 0.4$

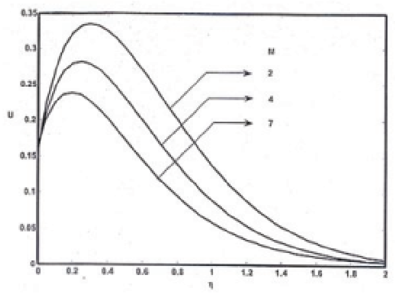

Fig. 18 Velocity versus η for $Pr = .71, Gr = 3, Gm = 3, Sc = .60, Sr = 0, N = 10, Q = 1, K = 10, t = 0.4$ (Figure 3 of the work Muthucumaraswamy and Sivkumar(2016)

Nomenclature

a^*	mean absorption coefficient
A	positive real constant
B_0	strength of applied magnetic field
$\vec{B}$	magnetic induction vector
C'	species concentration
C_p	specific heat at constant pressure
C'_w	dimensional species concentration at the plate
C'_∞	dimensional species concentration in the free stream
D_M	mass diffusion coefficient
D_T	thermal diffusion coefficient
erf	error function
$erfc$	complementary error function
g	acceleration due to gravity
Gm	solutal Grashof number
Gr	thermal Grashof number
$\vec{J}$	current density vector
K	chemical reaction parameter
K_1	chemical reaction rate
K_T	thermal diffusion ratio
M	Hartmann number
N	radiation parameter
Nu	Nusselt number
p	fluid pressure
Pr	Prandtl number
$\vec{q}$	fluid velocity vector
q_r	magnitude of radiative heat flux
Q	non-dimensional heat source parameter
Q'	dimensional heat source
Sc	Schmidt number
Sr	Soret number
t	dimensionless time
t'	dimensional time
T'	fluid temperature
T'_m	mean fluid temperature
$T'{}_\infty$	fluid temperature at free stream
$T'{}_w$	fluid temperature at the plate

u non-dimensional velocity component along x direction
u' x' component of fluid velocity
β coefficient of volume expansion for heat transfer
β_c coefficient of volume expansion for mass transfer
κ thermal conductivity
μ coefficient of viscosity
ν kinematic viscosity
ϕ dimensionless concentration
ρ fluid density
σ electrical conductivity
σ^* Stefan Boltzmann constant
τ skin friction coefficient
θ dimensionless temperature
and the other symbols have their usual meanings.

Appendix

$$A_1 = \frac{Sr\,Sc\,Pr}{Pr - Sc}, A_2 = \frac{Q\,Pr + R}{Pr}, A_3 = \frac{Sc\,K - (Q\,Pr + R)}{Pr - Sc},$$
$$A_4 = -\frac{A_1 A_2}{A_3}, A_5 = \frac{A_1\,(A_2 + A_3)}{A_3}, A_6 = \frac{Gr}{1 - Pr},$$
$$A_7 = \frac{Gc\,(1 + A_4)}{Sc - 1},\ A_8 = \frac{Gc\,A_5}{Sc - 1},\ A_9 = \frac{Gc\,A_4}{Pr - 1},$$
$$A_{10} = \frac{Gc\,A_5}{Pr - 1}, A_{11} = \frac{M - Pr\,A_2}{Pr - 1}, A_{12} = \frac{M - Sc\,K}{Sc - 1},$$
$$A_{13} = A_6 + A_9,\ A_{14} = \frac{A_{13}}{A_{11}}, A_{15} = \frac{A_7}{A_{12}},$$
$$A_{16} = \frac{A_8}{A_3 - A_{12}},\ A_{18} = \frac{A_{10}}{A_3 - A_{11}}, A_{19} = A_{18} - A_{14},$$
$$A_{20} = A_{14} - A_{15}, A_{21} = A_{15} - A_{16},\ A_{22} = A_{16} - A_{18},\ A_{23} = A_{14} - A_{18},$$
$$A_{24} = A_{16} - A_{15}, A_{25} = M + A_{11},\ A_{26} = M + A_{12},\ A_{27} = M + A_3,$$
$$A_{28} = A_2 + A_{11}, , A_{29} = K + A_{12},\ A_{30} = K + A_3,\ A_{31} = A_2 + A_3.$$

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