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Heat Source and Chemical Reaction Effects on the Unsteady Radiative Free Convection Flow of Conducting Fluid from an Impulsively Started Infinite Vertical Plate in the Presence of Magnetic Field

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Abstract: An investigation is made on the unsteady electrically conducting Newtonian fluid flow past a suddenly started vertical infinite flat plate under the influence of heat and mass transfer in the presence of magnetic field. The radiation and heat absorption effects are studied in this investigation. Mass diffusion are taken in to account the homogeneous chemical reaction of first order. By systematically transforming the governing set of partial differential equations into non dimensional form using selected similarity variables. An exact analytical solution is obtained from the dimensionless governing equations by using Laplace transform technique and inverse Laplace transform technique. The velocity, temperature and concentration profiles are presented for different existing flow parameters with the help of graphical representation. The velocity of the conducting fluid decreases with increasing magnetic parameter, heat absorption parameter, chemical reaction parameter and the velocity increases with increasing buoyancy parameter and time. The temperature of the fluid decreases with increasing the Prandtl number, heat absorption parameter and increases with increasing time. Similarly, the concentration of the fluid decreases with increasing the Schmidt number, chemical reaction parameter and increases with increasing time. The velocity, temperature and concentration profiles are studied for different existing parameters have been compared with earlier published works and the present results are found good agreement with the published results. The skin friction co-efficient, Nussult number and Sherwood number have also been calculated for all the existing parameters in this paper. Skin-friction decreases with increasing the magnetic parameter but skin friction increases with the increasing chemical reaction parameter, Prandtl number, Schmidt number, heat absorption parameter and time. No magnetic effect is observed on Nusselt and Sherwood number but with the increase of Prandtl number and Schmidt number, Nusselt number and Sherwood number are seen to increase respectively but both decrease with increasing time.

Keywords: Unsteady Flow, Vertical Late, Conducting Fluid, Magnetic Field, Heat Transfer, Mass Transfer

1. Introduction

In recent years of studies, the problems of MHD convective heat and mass transfer flow of conducting fluid have been attracted the attention of number of researchers because of their possible application in transportation cooling of re-entry vehicles and rocket boosters, in developing confinement schemes for controlled fusion, in aeronautics and missile aerodynamic. Ahmed [1] has discussed the Soret and radiation effects on transient MHD free convection from an impulsively started infinite vertical plate. To outline some of most relevant publications, boundary layer in thermal radiation, absorbing and emitting media was studied by Viskanta and Ghosh

[2].The significance of interaction of thermal radiation with conduction and convection heat transfer was received in the book by Cess [3] and Sparrow and Cess [4]. Chen and Chen [5] considered the problem of free convection flow of non-Newtonian powerlaw fluids along a vertical plate embeded in a porous medium. Hossain [6] presented the problem on unsteady MHD convective transfer past a semi-infinite vertical porous moving plate with variable plate temperature. Takhar et al. [7] and hossain et al. [8] investigated the effect of radiation on MHD free convection flow of a radiating gas past a semi-infinite vertical plate and a porous vertical plate respectively. Hossain et al. [9] also implemented the radiation effects of free convection flow of fluid with variable viscosity from a porous vertical plate. Effects on combined heat and mass transfer by natural convection in a vertical porous enclosure was presented by Kumar et al. [10]. Muthucumaraswammy and Kumar [11] has shown the effects of radiation when the vertical plate is moving in the presence of variable temperature and mass diffusion. Muthucumaraswamy and Janakriraman [12] have discussed mass transfer effects on isothermal vertical oscillating plate in the presence of chemical reaction . Ahmed and Sharma [13] analysed the joint effect of thermal radiation and transverse magnetic field on an unsteady convection and mass transfer flow of an incompressible, viscous, electrically conducting fluid past a suddenly fixed vertical plate. Ishak [14] worked mixed convection boundary layer flow over a horizontal plate with thermal radiation. Paul and Talukdar [15] discussed perturbation analysis of unsteady magneto-hydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. Soret and heat source effects on the unsteady radiative MHD free convective flow from an impulsively started infinite vertical plate has been discussed by Turkyilmazoglu and Pop [16]. Muthucumaraswamy and Radhakrishnan [17] have also investigated chemical reaction effects on flow past an accelerated vertical plate with variable temperature and mass diffusion in the presence of magnetic field. Sarki and Ahmed [18] forwarded an investigation on heat and Mass transfer with chemical reaction and exponential mass diffusion. Effect of radiation on MHD flow past an impulsively started vertical plate with variable heat and mass transfer has been analysed by Rajput and Kumar [19]. Nayak et al. [20] investigated Soret and Dufour effect on mixed convection unsteady MHD boundary layer flow over stretching sheet in porous medium with chemically reactive species. An Analytical solution for combined heat and mass transfer in laminar falling film absorption with uniform film velocity-adiabatic wall boundary has been discussed by Meyer [21]. Seth et al. [22] discussed heat and mass transfer effects on unsteady MHD natural convection flow of a chemically reactive and radiating fluid through a porous medium past a moving vertical plate with arbitrary ramped temperature. Furthermore, several authors have performed their researches on chemical reactions effects, heat and mass transfer on different flow model conducting and non conducting fluid, micro-polar fluid, second grade fluid, in the presence of magnetic field(including Hall effect) and inclined magnetic field using perturbation method, numerical methods, Laplace transform technique etc. An extensive amount of study [23-28, 34] has been performed recently to get an enhanced indulgent heat and mass transfer problem in various physical model for different existing flow parameters. Moreover,An enhancement of heat and mass transfer of a physical model using caputo fractional derivative of variable order and modified Laplace transform method was presented by Asjad et al. [29]. Choudhury et al. [30] investigated the effect of radiation on MHD flow past a porous vertical plate in the presence of heat sink and the same problem extended with constant heat flux and heat sink by Choudhury et al. [31].Recently, Phukan [32] forwarded an investigation on study of thermal buoyancy and concentration buoyancy effects on the electrically conducting fluid flow past an impulsively started vertical plate with temperature and mass diffusion in the presence of inclined magnetic field. Shah et al. [33] investigated dynamic of chemical reactive on magneto Hybrid Nano meterial with heat radiation due to porous exponential plate: Laplace transfom technique for heat and mass.

In this paper, it is proposed to investigate the chemical and heat absorption effects on unsteady flow past an impulsively started infinite vertical plate in the presence of magnetic field. The present work may be considered as an extension of Turkyilmazoglu and Pop [16] by considering the presence of chemical reaction.

In this analysis, analytical closed form solutions are derived by using Laplace and inverse Laplace transform technique for the momentum, energy and concentration equations assuming some proper change of variables. By means of the derived solutions, the flow field characteristics, the thermal and concentration, and hydrodynamics response of the system such as the physical importance of skin friction, heat transfer and mass transfer coefficients have been thoroughly investigated for different existing flow parameters in this paper.

2. Formulation of the Problem

We consider an unsteady radiative MHD free convective free convection and mass transfer flow of an electrically conducting, viscous, incompressible fluid past a suddenly moving vertical plate in the presence of a magnetic field of uniform strength B_0. The magnetic Reynolds number of the flow is taken to be so small that the induced magnetic field is become negligible. The concentration of the diffusivity species of the (binary mixture) fluid is assumed to be very small in comparison with the other chemical species which are present, and hence Soret and Dufour effects are negligible. The origin of the co-ordinates system is taken to be at any point of the flat vertical infinite plate, the x^* -axis is chosen along the plate vertically upward, and the y^*-axis is perpendicular to the plate. As the plate is considered infinite in the x^* -direction, and hence all physical quantities will be independent of x^* . So under these assumption, the physical variables are purely the function of y^* and t^* only. After neglecting the viscous dissipation, the problem can be governed by the set of following equations (under Boussinesqâs approximation) for conservation of mass, momentum, energy and concentration are as follows

$$\frac{\partial u^*}{\partial y^*} = 0, (v^* = 0 \; in \quad x^* - momentum\, equation). \quad (1)$$

$$\frac{\partial u^*}{\partial t^*} = \nu \frac{\partial^2 u^*}{\partial y^{*2}} + g\beta_t(T^* - T^*_\infty) + g\beta_m(C^* - C^*_\infty) - \frac{\sigma B_0^2}{\rho}u^*, \quad (2)$$

$$\frac{\partial T^*}{\partial t^*} = \frac{\kappa}{\rho\, C_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho\, C_p}\frac{\partial q}{\partial y^*} - \frac{Q(T^* - T^*_\infty)}{\rho\, C_p} \quad (3)$$

and

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - K_1(C^* - C^*_\infty). \quad (4)$$

The boundary conditions for velocity, temperature and species concentration are given as follows

$$\left.\begin{aligned} t^* \leq 0: \; u^* = 0, \; T^* = T^*_\infty, \; C^* = C^*_\infty, for\; all\; y, \\ t^* > 0, u^* = U_0, T^* = T^*_w, C^* = C^*_w, at\; y^* = 0, \\ u^* \to \infty, T^* \to T_\infty, \; C^* \to C^*_\infty \; as\; y^* \to \infty. \end{aligned}\right\} \quad (5)$$

where u^* is the velocity in the direction of x^* - axis, v^* is the velocity in the direction of y^* - axis, T^* is the temperature of the fluid, C^* is the species concentration in the fluid, T^*_w is the constant plate temperature with $T^*_w > T^*_\infty$ (heated plate), C^*_w is the species concentration at the surface of the plate, β_t is the thermal volume expansion, β_m is the concentration volume expansion, C_p is the specific heat at constant pressure, ρ is density of the fluid, ν is the kinematic viscosity of the fluid, g is the acceleration due to gravity, κ is the thermal conductivity of the conducting fluid, K_1 is the chemical reaction rate on the species concentration, Q is the heat source term denoting heat absorption for $Q > 0$ and heat generation $Q < 0$ (Here we have considered heat generation i.e. emitting heat from the source). Assuming the fluid is optically thin with a relativity low density and radiative heat flux is according to the ref as Cogley et al. [35] is given by

$$q_r = -\frac{4\sigma^*}{3\kappa^*}\frac{\partial T^{*4}}{\partial y^*}(t^*, y^*), \quad (6)$$

where σ^* is the Stefan- Boltzman constant and κ^* is the mean absorption coefficient. Considering the temperature difference within the flow sufficiently small i.e. (difference between fluid temperature and free stream temperature), T^{*4} can be expressed as the linear function of temperature. This is accomplished by expanding T^{*4} in a Taylor series about T^*_∞ and neglecting higher order terms, and we have

$$T^{*4} = 4\, T^{*3}_\infty\, T - 3\, T^{*4}_\infty. \quad (7)$$

Using equation (7) and (8), equation (3) reduces to

$$\frac{\partial T^*}{\partial t^*} = \alpha(1 + \frac{16\sigma^*}{3\kappa\kappa^*}T^{*3}_\infty)\frac{\partial^2 T^*_\infty}{\partial y^{*2}} - \frac{Q_0}{\rho\, C_p}(T^* - T^*_\infty). \quad (8)$$

We introduce the following non-dimensional variables

$$\left.\begin{aligned} t = \frac{U_0^2 t^*}{\nu}, \; y = \frac{U_0\, y^*}{\nu}, \; u = \frac{u^*}{U_0}, \\ \theta = \frac{(T^* - T^*_\infty)}{(T^*_w - T^*_\infty)}, \; \phi = \frac{(C^* - C^*_\infty)}{(C^*_w - C^*_\infty)}, \end{aligned}\right\} \quad (9)$$

where we take $U_0 = [g\beta_t((T^* - T^*_\infty)\nu]^{\frac{1}{3}}$, as the characteristic velocity.

Substituting (9) in to equation (2), (3) and (4), we obtain the following non-dimensional equation for momentum, energy and concentration as below

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + \theta + N\phi - Mu, \quad (10)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial y^2} - Q\theta, \quad (11)$$

and

$$\frac{\partial \phi}{\partial t} = \frac{1}{S_c}\frac{\partial^2 \phi}{\partial y^2} - K\phi, \quad (12)$$

where

$$\left.\begin{aligned} N = \frac{\beta_c(C^*_w - C^*_\infty)}{\beta_t(T^*_w - T^*_\infty)}, \; N_r = \frac{16\sigma^*}{3\kappa\kappa^*}T^{*3}_\infty, \; P_r = \frac{\nu}{\alpha(1 + N_r)}, \\ Q = \frac{Q_0\nu}{\rho\, C_p U_0^2}, \; K = \frac{K_1\nu}{U_0^2}, \; M = \frac{\sigma\, B_0^2}{\rho\, U_0^2}, \; S_c = \frac{\nu}{D}. \end{aligned}\right\} \quad (13)$$

Here P_r is the scaled Prandtl number taking in to account the effect of thermal radiation, S_c is the Schmidt number, N is the ratio of buoyancy forces due to the temperature and concentration, N_r is the radiation parameter, Q is the heat absorption or heat generation parameter and K is the chemical reaction parameter. It is to be noted that β_t is a positive quantity i.e. $\beta_t > 0$ while β_m may be taken as positive or negative. It is clear that thermal and concentration buoyancy forces act in the same direction and assist each other in driving the flow in the case $N > 0$ and they opposes each other when $N < 0$. The case N =0 stands for the situation where there is no buoyancy effect from mass diffusion.

The initial and boundary conditions (5) for the for the non-dimensional parameters are as follows

$$\left.\begin{aligned} t \leq 0: \; u = 0, \theta = 0, \; \phi = 0, for\; all\; y, \\ t > 0: u = 1, \theta = 1, \phi = 1, \; at\; y = 0, \\ u \to 0, \theta \to 0, \; \phi \to 0, \; as\; y \to \infty \end{aligned}\right\}. \quad (14)$$

It may be noted that equations (10)-(12) for $Q = K = 0$ are the same as those obtained by Phukan [32] recently.

3. Solution of the Problem

The non-dimensional governing equations (10)-(12) subject to the boundary conditions (14) have been solved by using usual Laplace transform technique along with the help of Hetnarski's [36] development made on Laplace transform and inverse Laplace transform technique.

In order to obtain the temperature distribution from the equation (11) for the existing parameter P_r and Q across the thermal boundary for any time t we need to take Laplace transform on both sides of (11) as bellow

$$\left.\begin{aligned} L[\frac{\partial\theta(y,t)}{\partial t}] &= L[\frac{1}{P_r}\frac{\partial^2\theta(y,t)}{\partial y^2} - Q\theta(y,t)] \\ \Rightarrow sL[\theta(y,t)] - \theta(0,y) &= \frac{1}{P_r}\frac{d^2L[\,\theta(y,t]}{dy^2} - QL[\,\theta(y,t)] \end{aligned}\right\}.$$

Using the boundary conditions (14), we have

$$\frac{d^2\bar{\theta}}{dy^2} - P_r(s+Q)\bar{\theta} = 0 \quad where\ \bar{\theta} = L[\theta(y,t)] \tag{15}$$

whose solution will be of the form

$$\bar{\theta}(y,t) = A_1 e^{y\sqrt{(s+Q)P_r}} + A_2 e^{-y\sqrt{(s+Q)P_r}}, \tag{16}$$

where A_1 and A_2 are constants. Using the above boundary condition (14), we get

$$L[\theta(y,t)] = L[1] = \frac{1}{s} = A_1 + A_2. \tag{17}$$

Since $\theta(y,t)$ is bounded for $y \to \infty$, so $\bar{\theta}(y,s)$ is also bounded for $y \to \infty$ and it follows that we must choose A_1 as Spiegel [37] page no. 97. So we have

$$L[\theta(y,t)] = L[0] = A_1. \tag{18}$$

Using (16), (17) and (18) in (15) we have

$$L[\theta(y,t)] = \frac{1}{s}e^{-y\sqrt{(s+Q)P_r}}. \tag{19}$$

Now taking inverse Laplace transform on both sides of (19), we have

$$\theta(y,t)] = L^{-1}[\frac{1}{s}e^{-y\sqrt{(s+Q)P_r}}].$$

As on Campbell and Foster [38] we have

$$\left.\begin{aligned} \theta(y,t) = \frac{1}{2}\Bigg[& e^{-y\sqrt{P_rQ}}\operatorname{erfc}\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{Qt}\right) \\ & + e^{y\sqrt{P_rQ}}\operatorname{erfc}\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{Qt}\right)\Bigg]. \end{aligned}\right\} \tag{20}$$

Similarly, we obtain the concentration of the conducting fluid from the solution of equation (12) by using Laplace transform technique, we have

$$L[\phi(y,t)] = \frac{1}{s}e^{-y\sqrt{(s+K)S_c}}, \tag{21}$$

and then again using inverse Laplace transform technique as bellow

$$\phi(y,t) = L^{-1}\left[\frac{1}{s}e^{-y\sqrt{(s+K)S_c}}\right]$$

$$\left.\begin{aligned} \Rightarrow \phi(y,t) = \frac{1}{2}\Bigg[& e^{-y\sqrt{S_cK}}\operatorname{erfc}\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} - \sqrt{Kt}\right) \\ & + e^{y\sqrt{S_cK}}\operatorname{erfc}\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} + \sqrt{Kt}\right)\Bigg]. \end{aligned}\right\} \tag{22}$$

which gives the concentration across the concentration boundary layer thickness for the Schmidt number S_c and chemical reaction parameter K .

In the same way, to obtain the dimensionless velocity of the conducting fluid for the magnetic parameter M , and N which is the ratio of buoyancy forces due to the temperature and concentration of the conducting fluid, we have taken Laplace transform on both sides of the equation (10) as follows

$$L[\frac{\partial u(y,t)}{\partial t}] = L[\frac{\partial^2 u(y,t)}{\partial y^2} + \theta(y,t) + N\phi(y,t) - Mu(y,t)],$$

we get

$$\left.\begin{aligned} \Rightarrow sL[u(y,t)] - u(y,t) &= \frac{d^2L[u(y,t)]}{dy^2} \\ +L[\theta(y,t)] + NL[\phi(y,t)] &- ML[u(y,t)]. \end{aligned}\right\} \tag{23}$$

Applying the boundary conditions (14), we get

$$\frac{d^2L[u(y,t)]}{dy^2} - (s+M)L[u(y,t)] = -L[\theta(y,t)] - NL[\phi(y,t)],$$

whose general solution will be of the form as below

$$L[u(y,t)] = A.E. + P.I. \tag{24}$$

where

$$A.E. = A_3 e^{y\sqrt{(s+M)}} + A_4 e^{-\sqrt{(s+M)}},$$

$$P.I. = -\frac{1}{D^2-(s+M)}L[\theta(y,t)] - \frac{N}{D^2-(s+M)}L[\phi(y,t)],$$

where A_3 and A_4 are arbitrary constants.

Substituting the values of $L[\theta(y,t)]$ and $L[\phi(y,t)]$ from (19) and (21) respectively in equation (24) we have

$$\left.\begin{aligned} L[u(y,t)] &= A_3 e^{y\sqrt{(s+M)}} + A_4 e^{-\sqrt{(s+M)}} \\ +\frac{1}{1-P_r}\frac{e^{-y\sqrt{(s+Q)P_r}}}{s(s-a)} &+ \frac{N}{1-S_c}\frac{e^{-y\sqrt{(s+K)S_c}}}{s(s-b)} \end{aligned}\right\}, \tag{25}$$

where $a = \frac{QP_r - M}{1-P_r}$ and $b = \frac{KS_c - M}{1-S_c}$.

Again using the boundary condition (14) we get

$$\left.\begin{aligned} L[u(y,t)] = L[1] = \frac{1}{s} = A_3 + A_4 \\ + \frac{1}{(1-P_r)s(s-a)} + \frac{N}{(1-S_c)s(s-b)}. \end{aligned}\right\} \quad (26)$$

Since $u(y,t)$ is bounded for $y \to \infty$, so $L[u(y,t)]$ i.e $u(y,s)$ is also bounded for $y \to \infty$ and it follows that we must choose A_3 as Spiegel [37] page no. 97. So we have

$$L[u(y,t)] = L[0] = 0 = A_3. \quad (27)$$

Using equation (26) and (27), equation (25) reduces to

$$\left.\begin{aligned} L[u(y,t)] = \frac{e^{-y\sqrt{s+M}}}{s} + \frac{1}{(1-P_r)} \frac{e^{-yP_r\sqrt{s+Q}} - e^{-y\sqrt{s+M}}}{s(s-a)} \\ + \frac{N}{(1-S_c)} \frac{e^{-yS_C\sqrt{s+K}} - e^{-y\sqrt{s+M}}}{s(s-b)}. \end{aligned}\right\}. \quad (28)$$

Taking inverse Laplace transform on both sides of (28) we get the solution for the velocity field as below

$$\left.\begin{aligned} u(y,t) = \frac{1}{2}\left\{ e^{-\sqrt{M}t}\text{erfc}\left(\frac{y}{2\sqrt{t}} - \sqrt{Mt}\right)\right. \\ \left. + e^{\sqrt{M}t}\text{erfc}\left(\frac{y}{2\sqrt{t}} + \sqrt{Mt}\right)\right\} \\ + \frac{e^{at}}{2a(1-P_r)}\left\{ e^{-y\sqrt{P_r(a+Q)}}\text{erfc}\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{(a+Q)t}\right)\right. \\ \left. + e^{y\sqrt{P_r(a+Q)}}\text{erfc}\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{(a+Q)t}\right)\right\} \\ - \frac{1}{2a(1-P_r)}\left\{ e^{-y\sqrt{P_rQ}}\text{erfc}\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{Qt}\right)\right. \\ \left. - e^{y\sqrt{P_rQ}}\text{erfc}\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{Qt}\right)\right\} \\ + \frac{Ne^{bt}}{2b(1-S_c)}\left\{ e^{-y\sqrt{S_c(b+K)}}\text{erfc}\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} - \sqrt{(b+K)t}\right)\right. \\ \left. + e^{y\sqrt{S_c(b+K)}}\text{erfc}\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} + \sqrt{(b+K)t}\right)\right\} \\ - \frac{N}{2b(1-S_c)}\left\{ e^{-y\sqrt{S_cK}}\text{erfc}\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} - \sqrt{Kt}\right)\right. \\ \left. - e^{y\sqrt{S_cK}}\text{erfc}\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} + \sqrt{Kt}\right)\right\}. \end{aligned}\right\} \quad (29)$$

4. Skin Friction , Nusselt Number and Sherwood Number

Physical quantities of interaction in the present discussion are the skin friction co-efficient C_f, the Nusselt number N_u and the Sherwood number (S_h, which are defined as $C_f = \frac{\tau_w}{\rho\nu^2}$, $N_u = \frac{\nu q_w}{U_0^2\kappa(T_w^* - T_\infty^*)}$ and $S_h = \frac{j_w\ \nu}{U_0 D_m(C_w^* - C_\infty^*)}$ respectively; where τ_w is the skin friction or shear stress, q_w and j_w are the heat and mass flux from the plate respectively; which are given by $\tau_w = -\mu(\frac{\partial u^*}{\partial y^*})_{y^*=0}$, $q_w = -\alpha(\frac{\partial T^*}{\partial y^*})_{y^*=0}$ and $J_w = -D_m(\frac{\partial C^*}{\partial y^*})_{y^*=0}$ respectively.

Using the non-dimensionless variables (9), the dimensionless physical parameters are derived as below

$$Skinfriction\ co-efficient : \tau_w = -\frac{\partial u(y,t)}{\partial y} = -u(0,t), \quad (30)$$

$$Nusselt\ number :\ N_u = -(\frac{\partial \theta(y,t)}{\partial t})_{y=0} = -\theta'(0,t) \quad (31)$$

and

$$Sherwood\ number :\ S_h = -(\frac{\partial \phi(y,t)}{\partial t})_{y=0} = -\phi'(0,t) \quad (32)$$

respectively, and these non-dimensionless physical parameters are analytically evaluated as follows

$$\left.\begin{aligned}\tau_w = &\frac{1}{2}\sqrt{M}[\mathrm{erfc}(\sqrt{Mt})-2)-\frac{e^{-Mt}}{\sqrt{\pi t}}]-\frac{1}{2}M\sqrt{P_rQ}\,\mathrm{erfc}(\sqrt{Qt}-2)\\ &+\sqrt{P_rQ}\,\mathrm{erfc}(\sqrt{Qt})-\frac{e^{-Qt}}{\sqrt{\frac{\pi P_r}{t}}}]\\ &-\frac{1}{2}[MN\sqrt{S_cK}\,\mathrm{erfc}(\sqrt{Kt}-2)\\ &+\sqrt{S_cK}\,\mathrm{erfc}(\sqrt{Kt})-\frac{e^{-Kt}}{\sqrt{\frac{\pi S_c}{t}}}]\\ &+\frac{1}{2}\sqrt{M}\,\mathrm{erfc}(\sqrt{Mt})\\ &+M[e^{-\frac{Mt}{S_c-1}}\sqrt{S_c(K-\frac{M}{S_c-1})}\,\mathrm{erfc}(\sqrt{(K-\frac{M}{S_c-1})t}-2)\\ &+\sqrt{S_c(K-\frac{M}{S_c-1})}\,\mathrm{erfc}(\sqrt{(K-\frac{M}{S_c-1})t})-\frac{e^{t(K-\frac{M}{S_c-1})}}{\sqrt{\frac{\pi S_c}{t}}}]\\ &+\frac{M}{2}[e^{-\frac{Mt}{P_r-1}}\sqrt{P_r(Q-\frac{M}{P_r-1})}\,\mathrm{erfc}(\sqrt{(Q-\frac{M}{P_r-1})t}-2)\\ &+\sqrt{S_c(Q-\frac{M}{S_c-1})}\,\mathrm{erfc}(\sqrt{(K-\frac{M}{S_c-1})t})-\frac{e^{-t(Q-\frac{M}{P_r-1})}}{\sqrt{\frac{\pi P_r}{t}}}],\end{aligned}\right\} \tag{33}$$

$$N_u=\frac{1}{2}\sqrt{P_rQ}\mathrm{erfc}(\sqrt{\mathrm{Qt}}-2)+\frac{1}{2}\sqrt{P_rQ}\mathrm{erfc}(\sqrt{\mathrm{Qt}}-\frac{\sqrt{P_r}}{\sqrt{\pi}\,t}e^{-Qt}, \tag{34}$$

and

$$S_h=\frac{1}{2}\sqrt{S_cK}\mathrm{erfc}(\sqrt{\mathrm{Kt}}-2)+\frac{1}{2}\sqrt{S_cK}\mathrm{erfc}(\sqrt{\mathrm{Kt}}-\frac{\sqrt{S_c}}{\sqrt{\pi}\,t}e^{-Kt}, \tag{35}$$

respectively .

5. Results and Discussion

The values of skin friction coefficient, Nusselt number and Sherwood numbers calculated from (30)-(32) using (33)-(35) respectively for different existing flow parameters are tabulated in Tables 1-7. It is clearly observed from Table-1 that magnitude of skin-friction co-efficient decreases as the magnetic parameter M but skin friction increases with the increase of chemical reaction parameter K, Prandtl number P_r, Schmidt number S_c , of heat absorption parameter Q and time t as observed in Table-2, Table-4, Table-5, Table-6 and Table-7 respectively. No magnetic effect is observed on Nusselt N_u and Sherwood number S_h; but with the increase of Prandtl number P_r and Schmidt number S_c, Nusselt number and Sherwood number are seen to increase as shown in Table-4 and Table-5 respectively. The magnitude of skin-friction co-efficient also increases with the increase of chemical reaction parameter K and heat absorption parameter Q as shown in Table -2 and Table-6 respectively. The effect of Prandtl number P_r is seen to increase the Nuseelt number in Table-2.The magnitude of skin friction are seen to decrease with the increase of concentration buoyancy parameter N and time t as shown in the Table-3 and no effects are observed in Nusselt number and Sherwood number It is clearly observed from Table-7 that skin friction coefficient increase with increase of time t but Nusselt number and Sherwood number decrease with time t. It is clearly observed from all Tables 1-6 that the values of skin friction, Nusselt number and Sherwood number converses only for small dimensionless time $t = 0.2$.. Moreover, values of skin friction, Nusselt number and Sherwood number converges smoothly for the dimensionless time t in the domain $0 < t \leq 0.6$ as seen in Table 7.

Numerical evaluation of the results obtained for the dimensionless velocity, temperature and concentration of the conducting fluid by using Laplace transform technique reported in the previous section was performed and a representative set of graphical results are shown in Figs 1 a-3 c and Figure 5a, b . These results are plotted to illustrate the influence of different existing flow parameters on the dimensionless velocity, temperature and concentration profiles of the conducting fluid across the boundary layer thickness. Figure 1a presents the typical profiles of the dimensionless velocity across the boundary layers for different magnetic parameter M and can be seen that effect of magnetic parameter M is to decrease the velocity of the conducting fluid across the boundary layer. Since the magnetic field is used perpendicular to the motion of the conducting fluid so according to Fleming left hand rule, a ponder motive force called Lorentz force exist which retards the motion of the fluid. That is, the higher of magnetic parameter M implies higher of Lorentz force which slow down the motion of the fluid in the boundary layer. Figure 1b shows the effect of Prandtl number P_r on the dimensionless temperature and it can be seen to decrease the temperature of the fluid. This is due to the fact that the thermal boundary layer thickness decreases with the increase of Prandtl number P_r. From Figure 1c the effect of Schmidt number S_c is observed to decrease the concentration in the boundary layer. This happens due to the fact that when Schmidt number S_c increases the molecular diffusion of the mixture decreases and conversely, S_c decreases with molecular diffusion increases. So concentration boundary layer thickness decreases with increases of S_c. *Figure* 2a depicts to show the effect of heat absorption parameter Q on the dimensionless temperature of the fluid. It is seen that the temperature decreases with the increase of Q. Physically, the thermal boundary layer thickness decrease with increasing the value of heat absorption parameter Q. The effect of chemical reaction parameter K on the concentration of the fluid is shown in Figure 2b It is clear from the Figure 2b that concentration decreases with the increase of Chemical reaction parameter K across the concentration boundary layer thickness. Figs 2c , Figure 3a and Figure 3b show that dimensionless velocity, temperature and concentration for different values time t. Also it can be clear from Figs 2 c , Figure3 a and Figure 3b that velocity, temperature and concentration increase with increasing value of time t across the boundary layer of the conducting fluid. The effect of buoyancy parameter N is to increase the velocity profiles across the boundary layer region as shown in Figure3 c. In Figure 4a, Figure 4b and Figure 4c are shown to compare the temperature and concentration for different heat absorption parameters, Schmidt number and chemical reaction parameter with earlier different published works [16, 17] and [12]. Figure 5a and Figure 5b demonstrate the typical profiles of velocity for different chemical reaction parameter K and heat absorption parameters Q respectively. The effects of both parameters K and Q are to decrease the velocity of the conducting fluid as in this phenomenon because for the both parameters K and Q, the boundary layers thickness decrease with increasing values of chemical reaction parameter K and heat absorption parameter Q. The temperature of the conducting fluid for different Prandtl number P_r in absence of heat absorption parameter i.e. $Q = 0$ corresponds to the result presented by Muthucumaraswamy and Radhakrishnan [17] which is shown in Figure 5c.

6. Validation of the Results

To assure the validity of the present results need to compare with earlier published work. If we study the temperature field of present result in absence of chemical reaction parameter i.e. $K = 0$, then the result correspond to the result [15] as shown in Figure 4a when $M = 2$. That is, temperature θ of the conducting fluid for different heat absorption parameter Q across the thermal boundary layer in absence of chemical reaction parameter are good agreement with result of Turkyilmazoglu and Pop [16]. The concentration ϕ of the conducting fluid for different Schmidt number S_c in absence of heat absorption parameter i.e. $Q = 0$, is shown in Figure 4b for fixed magnetic parameter $M = 2$ and this result excellently agrees with results presented by Muthucumaraswamy and Radhakrishnan [17]. Further more, the concentration ϕ of the fluid for different chemical reaction parameter K is shown in Figure 4c in absence of magnetic field parameter and heat absorption parameter i.e. $M = 0$ and $Q = 0$. The results presented in Figure 4c are in good agreement with the result presented by Muthucumaraswamy and Janakriraman [12].

7. Concluding Remark

This worked studied the heat absorption parameter and chemical reaction parameters effects on the unsteady radiative free convection flow of conducting fluid from an impulsively started infinite vertical plate in the presence first order homogeneous chemical reaction. The governing partial differential equations were transformed in to non-dimensional partial differential equations and were solved by using Laplace and inverse Laplace transform technique. The following conclusions have been drawn from the present analytical study

1. The dimensionless velocity profiles is observed to reduce with increasing the magnetic parameter, heat absorption parameter, chemical reaction parameter and the same velocity increases with increasing the concentration buoyancy parameter and time t across the boundary layer.
2. Increasing the Prandtl number reduces the temperature profiles at the far field and concentrates the heat near the wall. Moreover, reduction is generated by increasing heat absorption parameter. The temperature of the fluid is increased with increasing the time t.
3. Concentration of the fluid is reduced with increasing Schmidt number and chemical reaction parameter but concentration increases with increasing the time t.
4. Skin friction increases with increasing the heat absorption parameter, Prandtl number, Chemical reaction parameter, Schmidt number and time t and skin friction decreases with increasing the magnetic parameter and concentration buoyancy parameter.
5. Nusselt number and Sherwood number are observed to decrease with increasing time t. Nusselt number is observed to increase with increasing the Prandtl number and heat absorption parameter.
6. Sherwood number is seen to increase with increasing the Schmidt number and chemical reaction parameter.

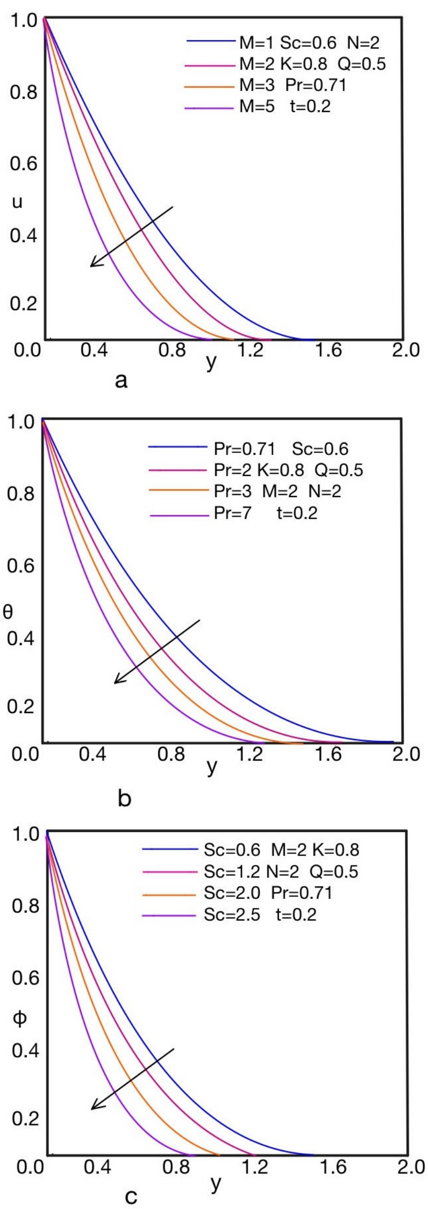
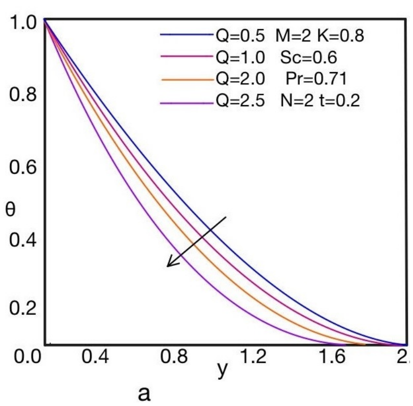


Figure 1. *a) Velocity profiles for different magnetic Parameter M. b) Temperature profiles for different Prandtl number P_r. c) Concentration profiles for different Schmidt number S_c.*



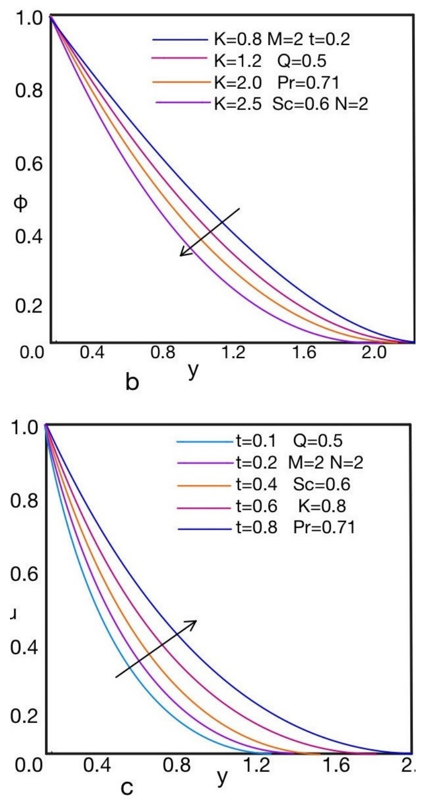
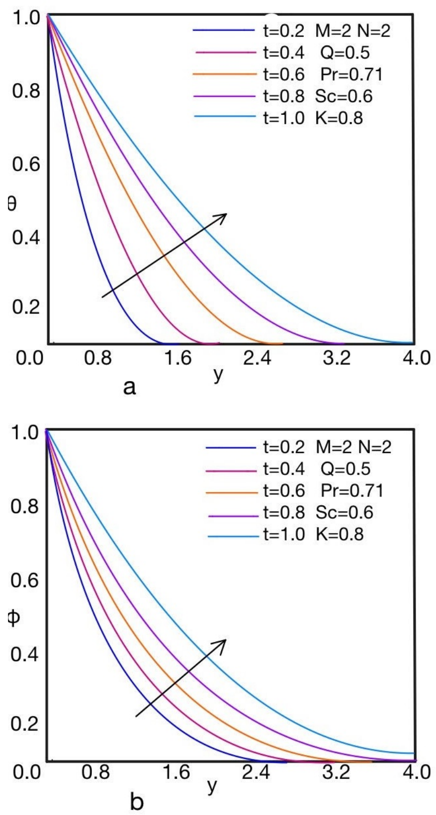


Figure 2. *a) Temperature profiles for different heat absorption parameter Q. b) Concentration profiles for different chemical reaction parameter K. c) Velocity profiles for different time t.*



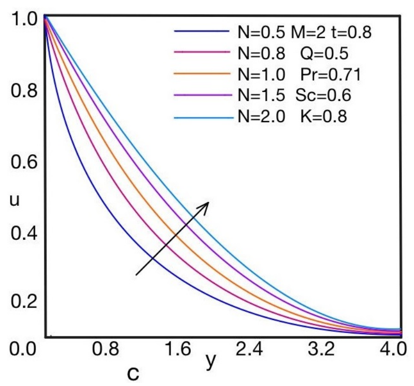


Figure 3. *a) Temperature profiles for different time t. b) Concentration profiles for different time t. c) Velocity profiles for different buoyancy parameter N.*

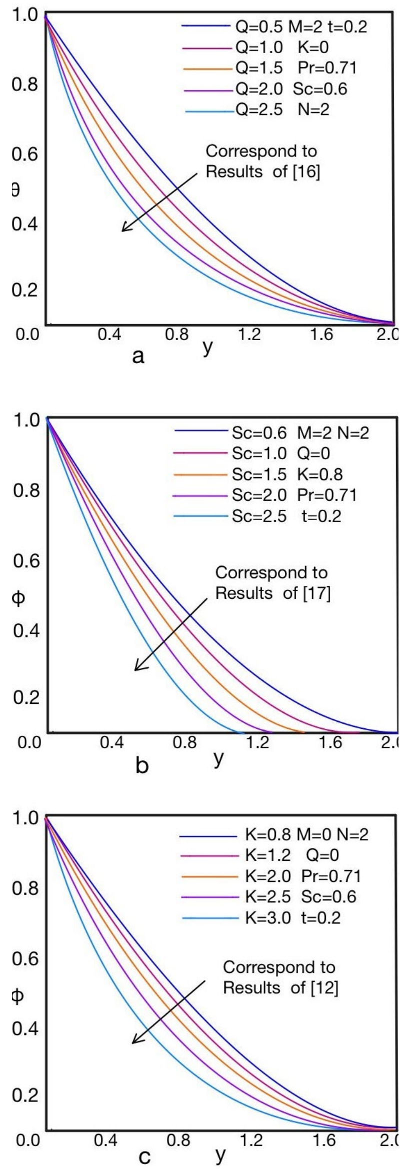


Figure 4. *a) Temperature profiles for different heat absorption parameter Q b) Concentration profiles for different Schmidt number S_c. c) Concentration profiles for different chemical reaction parameter K.*

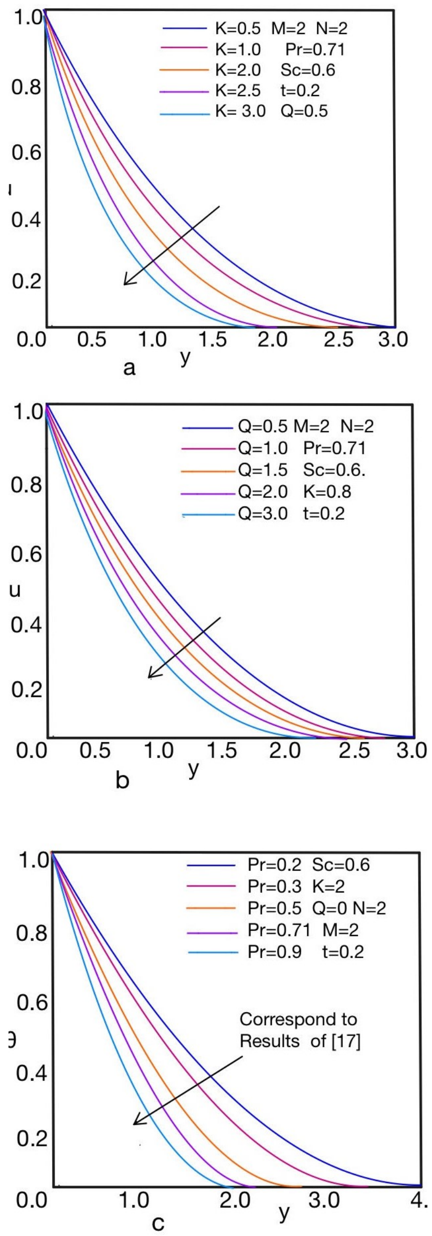


Figure 5. *a) Velocity profiles for different chemical reaction parameter K. b) Velocity profiles for different heat absorption parameter Q. c) Temperature profiles for different Prandtl number P_r.*

Table 1. *Effects of magnetic parameter M on Skin friction, Nusselt number and Sherwood number for $P_r = 0.71$, $S_c = 0.6$, $K = 1$, $N = 1$, $Q = 0.5$, and $t = 0.2$.*

M	τ_w	Nu	S_h
0	93.1677	1.1676	1.3440
1	26.6874	1.1676	1.3440
2	5.4734	1.1676	1.3440
5	1.2616	1.1676	1.3440
7	0.2158	1.1676	1.3440

Table 2. *Effects of chemical reaction parameter K on skin friction, Nusselt number, and Sherwood number for $P_r = 0.71$, $S_c = 0.6$, $M = 2$, $N = 1$, $Q = 0.5$, and $t = 0.2$.*

k	τ_w	Nu	S_h
0.6	26.1482	1.1676	1.0922
1	26.3048	1.1676	1.1664
2	26.6874	1.1676	1.3440
3	27.0578	1.1676	1.5112
5	27.7656	1.1676	1.8191

Table 3. *Effects of concentration buoyancy parameter N on skin friction, Nusselt number, and Sherwood number for $P_r = 0.71$, $S_c = 0.6$, $K = 1$, $M = 2$, $Q = 0.5$, and $t = 0.2$.*

N	τ_w	Nu	S_h
1	26.6874	1.1676	1.3440
2	24.8729	1.1676	1.3440
3	23.0583	1.1676	1.3440
5	19.4292	1.1676	1.3440

Table 4. *Effects of Prandtl number P_r on skin friction, Nusselt number and Sherwood number for $M = 2$, $S_c = 0.6$, $K = 1$, $N = 1$, $Q = 0.5$, and $t = 0.2$.*

P_r	τ_w	Nu	S_h
0.1	11.4387	1.1676	1.3440
0.2	12.0863	1.1676	1.3440
0.5	15.5800	1.1676	1.3440
0.71	26.6874	1.1676	1.3440

Table 5. *Effects of Schmidt number S_c on skin friction, Nusselt number and Sherwood number for $P_r = 0.71$, $M = 2$, $K = 1$, $N = 1$, $Q = 0.5$, and $t = 0.2$.*

S_c	τ_w	Nu	S_h5
0.1	19.0455	1.1676	0.5487
0.3	20.5764	1.1676	0.9503
0.6	26.6874	1.1676	1.3440
0.8	60.8681	1.1676	1.5519
0.9	109.71	1.1676	1.6446

Table 6. *Effects of heat absorption parameter Q on skin friction, Nusselt number and Sherwood number for $P_r = 0.71$, $S_c = 0.6$, $K = 1$, $N = 1$, $M = 2$, and $t = 0.2$.*

Q	τ_w	Nu	S_h
0.5	26.6874	1.1676	1.3440
1	27.0416	1.2688	1.3440
1.5	27.3901	1.3669	1.3440
2	27.7332	1.4620	1.3440
3	28.4040	1.6439	1.3440
5	29.4513	1.6439	1.3440

Table 7. *Effects of time t on skin friction, Nusselt number and Sherwood number for $P_r = 0.71$, $S_c = 0.6$, $K = 1$, $N = 1$, $Q = 0.5$, and $M = 2$.*

t	τ_w	Nu	S_h
0.1	13.052	1.5779	1.6495
0.3	52.1405	0.9950	1.2339
0.5	191.7288	0.8337	1.1505
0.6	367.3015	0.7892	1.1325

Abbreviations

MHD	Magneto-hydrdynamics
et al.	Others
Figure	Figure

Roman symbols

B_0	Uniform Magnetic Field
C	Concentration
C_p	Specific Heat at Constant Pressure
D	Co-efficient of Mass Diffusivity
g	Acceleration due to Gravity
K	Chemical Reaction Parameter
k	Thermal Conductivity of the Fluid
M	Magnetic Field Parameter
N	Ratio of Buoyancy Forces Due to the Temperature and Concentration
N_r	Radiation Parameter
N_u	Nusselt Number
P_r	Scaled Prandtl Number
Q	Heat source Term
q_r	Radiative Flux
S_c	Schmidt Number
S_h	Sherwood Number
T	Temperature
t	Dimensionless Time
U_0	Characteristic Velocity
u, v	Component of Velocities Along and Perpendicular to the Plate
x, y	Distances Along and Perpendicular to the Plate Respectively

Greek symbols

α	Thermal Diffusivity
β_m	Concentration Expansion Co-efficient
β_t	Thermal Expansion Co-efficient
ρ	Density of Fluid
σ	Electrical Conductivity of the Fluid
σ^*	Stefan- Boltzman Constant
κ^*	Mean Absorption Coefficient
μ	Dynamic Viscosity
ν	Kinematic Viscosity
θ	Dimensionless Temperature
ϕ	Dimensionless Concentration

Superscripts

$'$	Differentiation with Respect to Y
$*$	Dimensional Properties

Subscripts

w	Wall Condition
∞	Free Stream Condition

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Author Contributions

Deva Kanta Phukan is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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Biography

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