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Abstract

The present paper deals with the theoretical study of thermal radiation and chemical reaction on free convective heat and mass transfer flow of a Newtonian viscous incompressible fluid past a suddenly accelerated semi–infinite vertical permeable plate immersed in Darcian absorption media. The fluid media is considered as optically thick and the Rosselend radiative heat flux model is incorporated in the energy equation. The governing equation of motions are first non-dimensionalised and then transformed into a set of ordinary differential equations by employing a suitable periodic transformation. The closed form of the expression for velocity, temperature and concentration fields as well as skin- friction, Nusselt and Sherwood numbers are obtained in terms of various physical parameters present. The effect of parameters like thermal radiation, first order chemical reaction, radiation absorption co-efficient and permeability parameter on the flow variables are obtained numerically and illustrated through graphs and tables. It is observed that, the absorption parameter and radiation parameter increase the temperature as well as the fluid velocity, while the skin–friction is found to be decreasing due to an increase in thermal radiation parameter. It is also observed that, some of the transportation phenomena accelerate due to the presence of chemical reaction parameter.

Keywords: Free convection, porous media; absorption fluid; impulsively accelerated plate thermal radiation; chemical reaction; radiation absorption

MSC 2010 No.: 76D05, 80A20

Nomenclature

$\bar{C}$	Species concentration
c_p	Specific heat at constant pressure
$\bar{C}_m$	Mean Species concentration at the plate
$\bar{C}_\infty$	Species concentration in the free stream
D_M	Co-efficient of mass diffusion
Gm	Thermal Grashof number
Gr	Solutal Grashof number
k	Thermal conductivity
Nu_R	Nusselt number (Real part)
Pr	Prandtl number
R	Radiation parameter
S	First-order Heat source parameter
Sc	Schmidt number
Sh_R	Sherwood number (Real part)
Sr	Soret number
t	Time variable (Non-Dimensional)
$\bar{t}$	Time variable (Dimensional)
$\bar{T}$	Fluid temperature
$\bar{T}_m$	Mean Temperature at the plate
$\bar{T}_\infty$	Temperature in the free stream
u	First component of fluid velocity (Non-Dimensional)
u_0	Mean plate velocity (Non-dimensional)
u_R	Real part of u
$\bar{u}$	First component of fluid velocity (Dimensional)
U_0	Mean plate velocity (Dimensional)
y	y – co-ordinate (Dimensional)

$\bar{y}$ y – co-ordinate (Non-Dimensional)

v Second component of fluid velocity (Non-Dimensional)

$\bar{v}$ Second component of fluid velocity (Dimensional)

V_0 Mean suction velocity

Greek Symbols

β Thermal Coefficient of volumetric expansion

β^* Solutal Coefficient of volumetric expansion

ρ Fluid density

ν Kinematic coefficient of viscosity

θ Non-dimensional temperature

θ_R Real part of θ

ϕ Non-dimensional species concentration

ϕ_R Real part of ϕ

τ_R Non-dimensional skin friction (Real part)

ω Frequency of Oscillation

Subscripts

m Mean / Average condition

∞ Free stream conditions

1. Introduction

The phenomena of heat and mass transfer involving free convection flow occurs frequently in several areas of chemical engineering and manufacturing processes and also in environmental problems, where the difference between air and soil temperature can give rise to complex flow patterns. On the other hand research in porous media has substantially increased in recent times due to its various practical applications and as such transport processes in porous media continue to play a significant role in several areas of applications, such as geo-mechanics, soil mechanics, petroleum engineering, hydrogeology, geophysics, and material sciences. For the last two decades or more, the problems of free convective heat and mass transfer flows through porous media have attracted the attention of a number of researchers because of their possible applications in many branches of science and technology, like in transportation, cooling of re-entry vehicles and rocket boosters, cross-hatching on ablative surfaces, and film vaporization in combustion chambers. Researchers like Vafai and Tien (1981), Bejan (1987), Jang and Ni (1989), Kim and Vafai (1989), Thakar and Soundalgekar (1991) etc. contributed significantly in the aforesaid area. Makinde (2009) considered the MHD boundary layer flow and mass transfer past a vertical plate in a porous medium with constant heat flux. Recently, Ahmed et al. (2013) considered the problem of free convection mass transfer flow past an oscillating plate in porous media with Soret effect.

All significant research work has been done on an impulsively started vertical plate under different boundary conditions depending upon the physical situation of the problem. Sengupta (2011) considered the case of free convection mass transfer flow past a uniformly accelerated plate with Soret and heat sink effects. Besides the aforesaid work, various researchers also contributed to viscous flow past an impulsively started plate Soundelgekar (1977, 1979), Raptis and Sing (1985), Muthucumaraswamy and Ganesan (1998, 1999) and Muthucumaraswamy et al. (2001) are worth mentioning.

The science of thermal radiation has become of increasing importance in aerospace research and design due to high temperatures associated with increased engine efficiencies. The theory of radiative heat transfer flow contributes substantially to the study of furnaces, combustion chambers and energy emissions from a nuclear explosion and in manufacturing industries for the design of fins, steel rolling, nuclear power plants, gas turbines, various propulsion devices for missiles, satellites, space vehicles etc. The pioneering work in the field of radiation was made by Cess (1966). Hossain and Thakkar (1996) considered the effect of radiation on mixed convection flow along a vertical plate with uniform surface temperature. Pathak et al. (2006) studied the effect of radiation on unsteady free convection flow bounded by an oscillating plate with variable wall temperature. The case of radiative mixed convection mass transfer flow past an iso - thermal porous plate in presence of thermal diffusion and heat generation was investigated by Sengupta (2012). Very recently Oahimire and Olajuwon (2014) studied the effects of radiation absorption and thermo-diffusion on MHD heat and mass transfer flow of a micro-polar fluid in the presence of the heat source.

On the other hand combined heat and mass transfer problems with chemical reactions are of importance in many processes, and have received a considerable amount of attention in recent years. A notable contribution in chemical reactions phenomena was made by Astarita (1967). Jaiswal and Soundalgekar (2001) studied mass transfer and chemical reaction for an oscillating flow of a viscous incompressible fluid past an infinite vertical porous plate with variable suction. Takhar et al. (2000) considered the flow and mass transfer on a stretching sheet in a magnetic field and chemically reactive specimen. Effects of chemical reaction, heat and mass transfer along a wedge with heat source and concentration in the presence of suction or injection were examined by Kandasamy et al. (2006). Seddeek et al. (2007) investigated the effects of chemical reaction and variable viscosity on hydro-magnetic mixed convection heat and mass transfer for Hiemenz flow through porous media with radiation. The combined effects of first order chemical reaction and radiation absorption on free convection flow through a porous medium with variable suction in the presence of uniform magnetic field was considered by Sudheer and Satyanarayana (2009). Seddeek and Almushigeh (2010) considered the effects of radiation and variable viscosity on MHD free convective flow and mass transfer over a stretching sheet with chemical reaction. The case of unsteady convection with chemical reaction and radiative heat transfer past a porous plate moving through a binary mixture was extensively studied by Makinde et al. (2011).

The objective of the present study is to consider the physical effects of thermal radiation, first order chemical reaction on a two- dimensional unsteady flow of a viscous chemically absorption fluid past a suddenly accelerated plate immersed in porous media with oscillating plate temperature and concentrations.

2. Mathematical Formulation of the Problem

Consider the free convective heat and mass transfer flow of a Newtonian incompressible viscous fluid through a semi-infinite vertical plate embedded in uniform Darcy porous media.

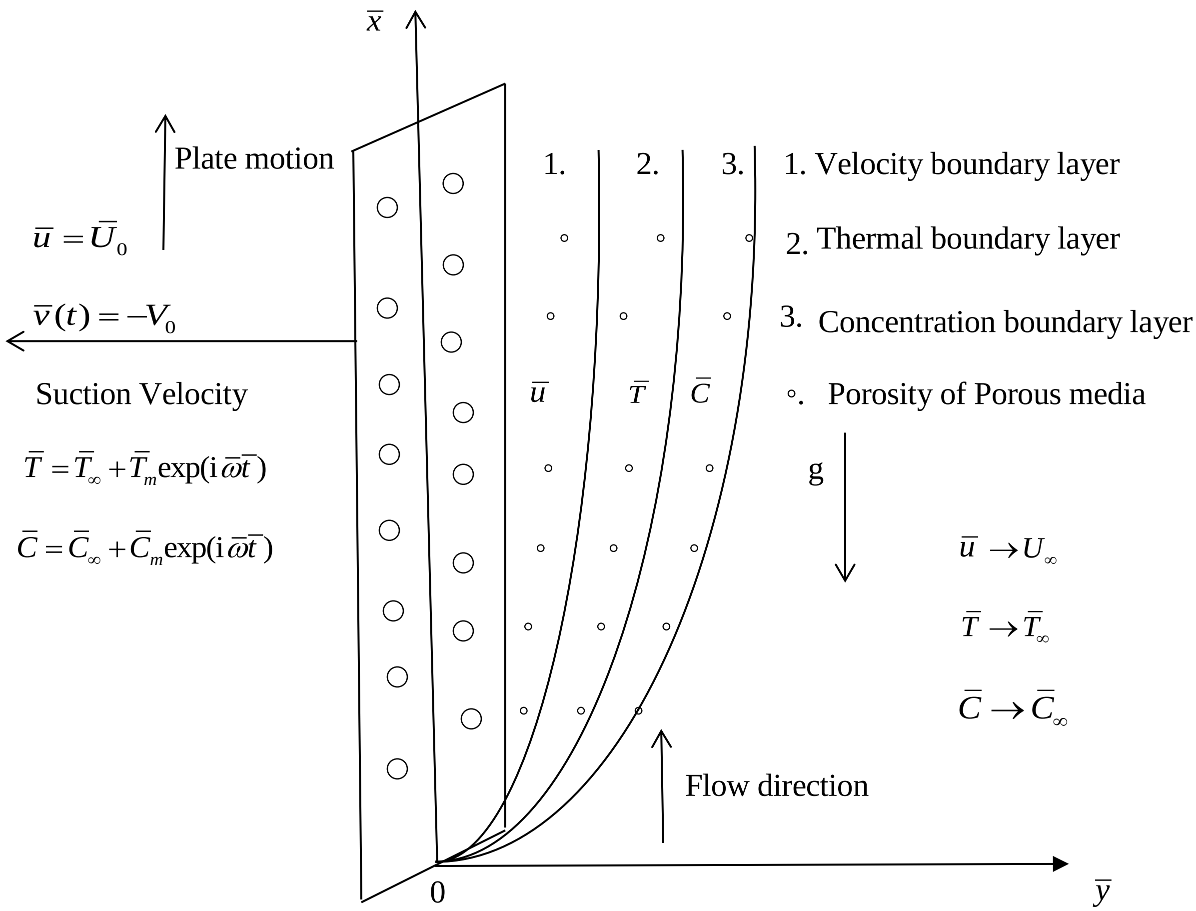

Figure 1. Schematic representation of flow configuration and co-ordinate system

Assume that the fluid as well as the porous media have constant physical properties and that both the fluid flow and the permeability of the medium are considered to be moderate as such, the Forchheimer flow model is not applicable for the study. The flow is considered to be unsteady, laminar and two-dimensional, whereas the fluid and the porous media are in local thermo-dynamical equilibrium. A co-ordinate system ($\bar{x}$, $\bar{y}$) has been introduced, with its $\bar{x}$ -axis along the length of the plate in the upward vertical direction and $\bar{y}$ - axis is placed perpendicular to the plate towards the fluid region. The plate is subjected to a constant suction velocity. Using the Boussinesq and boundary layer approximations, a two- dimensional fluid model has been developed in terms of a system of coupled partial differential equations, combined with a two-point semi-open initio - boundary conditions as follows:

Continuity Equation

$$\frac{\partial \bar{v}}{\partial \bar{y}} = 0 . \tag{1}$$

Momentum Equation

$$\frac{\partial \bar{u}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}} = \nu \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + g\beta(\bar{T} - \bar{T}_\infty) + g\beta^*(\bar{C} - \bar{C}_\infty) - \frac{\nu \bar{u}}{\bar{K}} . \tag{2}$$

Energy Equation

$$\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{T}}{\partial \bar{y}} = \frac{k}{\rho c_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} - \frac{1}{\rho c_p}\frac{\partial \bar{q}_{r\bar{y}}}{\partial \bar{y}} + \frac{\bar{Q}_l}{\rho c_p}(\bar{C} - \bar{C}_\infty) . \tag{3}$$

Species Continuity Equation

$$\frac{\partial \bar{C}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{C}}{\partial \bar{y}} = D_M \frac{\partial^2 \bar{C}}{\partial \bar{y}^2} - K_l(\bar{C} - \bar{C}_\infty) . \tag{4}$$

The relevant initio - boundary conditions:

$$\begin{gathered} \bar{u} = 0,\ \bar{T} = \bar{T}_\infty,\ \bar{C} = \bar{C}_\infty, \text{ for every } \bar{y} \text{ and when } \bar{t} \le 0, \\ \bar{u} = U_0, \bar{T} = \bar{T}_\infty + \bar{T}_m \exp(i\bar{\omega}\bar{t}), \bar{C} = \bar{C}_\infty + \bar{C}_m \exp(i\bar{\omega}\bar{t}), \\ \text{at } \bar{y} = 0, \text{ when } \bar{t} > 0, \\ \bar{u} \to 0, \bar{T} \to \bar{T}_\infty,\ \bar{C} \to \bar{C}_\infty, \\ \text{for } \bar{y} \to \infty, \text{ when } \bar{t} > 0. \end{gathered} \tag{5}$$

The constant suction velocity can be considered as:

$$\bar{v}(t) = -V_0 . \tag{6}$$

The Rosseland approximate model, which quantifies the radiative heat flux for an optically thick boundary layer flow in a simplified differential form, is considered as:

$$\bar{q}_r = -\frac{4\sigma^*}{3k^*}\frac{\partial \bar{T}^4}{\partial \bar{y}}, \tag{7}$$

where σ^* and k^* are the Stefan-Boltzmann constant and the Rosseland mean absorption coefficient, respectively. Assuming that the temperature differences within the flow are sufficiently small, as such $\bar{T}^4$ may be expressed as a linear function of the temperature $\bar{T}$ and expanding $\bar{T}^4$ in a Taylo series about $\bar{T}_\infty$ and neglecting higher order terms we, thus, get

$$\bar{T}^4 \approx \bar{T}_\infty^{\ 4} + (\bar{T} - \bar{T}_\infty)4\bar{T}_\infty^{\ 3} = 4\bar{T}_\infty^{\ 3}\bar{T} - 3\bar{T}_\infty^{\ 4}. \tag{8}$$

Using (8) and (7), equation (3) becomes,

$$\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{T}}{\partial \bar{y}} = \frac{k}{\rho c_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \frac{16\sigma^* \bar{T}_\infty^{\ 3}}{3\rho c_p k^*}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \frac{\bar{Q}_l}{\rho c_p}(\bar{C} - \bar{C}_\infty). \tag{9}$$

We introduce the following non-dimensional quantities:

$$y = \frac{\bar{y}V_0}{\nu}, t = \frac{\bar{t}V_0^{\ 2}}{\nu}, u = \frac{\bar{u}}{U_0}, v = \frac{\bar{v}}{V_0}, \theta = \frac{\bar{T} - \bar{T}_\infty}{\bar{T}_m},$$
$$\phi = \frac{\bar{C} - \bar{C}_\infty}{\bar{C}_m}, Gr = \frac{g\beta\nu\bar{T}_m}{U_0 V_0^{\ 2}}, K = \frac{V_0^{\ 2}\bar{K}}{\nu^2},$$
$$Gm = \frac{g\beta^*\nu\bar{C}_m}{U_0 V_0^{\ 2}}, \omega = \frac{\bar{\omega}\nu}{V_0^{\ 2}}, \Pr = \frac{\nu\rho c_p}{k}, Sc = \frac{\nu}{D_M},$$
$$R = \frac{4\sigma^*\bar{T}_\infty^{\ 3}}{kk^*}, N_r = \frac{\bar{Q}_l \nu}{kV_0^{\ 2}}, F = \frac{\bar{K}_l \nu}{V_0^{\ 2}}.$$

The corresponding non-dimensional form of equations (2), (9) and (4), respectively, become

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

$$\Pr\left(\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial y}\right) = \lambda\frac{\partial^2 \theta}{\partial y^2} + N_r\phi, \tag{11}$$

$$Sc\left(\frac{\partial \phi}{\partial t} - \frac{\partial \phi}{\partial y}\right) = \frac{\partial^2 \phi}{\partial y^2} - FSc\phi. \tag{12}$$

The non-dimensional initio - boundary conditions are:

$$\begin{aligned} &u=0,\ \theta=0,\ \phi=0, \text{ for every } y \text{ when } t\le 0, \\ &u=1,\ \theta=\exp(i\omega t),\ \phi=\exp(i\omega t) \text{ at } y=0 \text{ when } t>0, \\ &u\to 0, \theta\to 0,\ \phi\to 0, \text{ for } y\to\infty \text{ when } t>0. \end{aligned} \tag{13}$$

3. Method of Solution

To, get an exact closed analytical form of solutions; we prefer to use the technique of the normal mode method. For purely an oscillating flow, the form of solutions for expressions (8), (9) and (10) can taken as:

$$\begin{aligned} u(y,t) &= u_0(y)\exp(i\omega t), \\ \theta(y,t) &= \theta_0(y)\exp(i\omega t), \\ \phi(y,t) &= \phi_0(y)\exp(i\omega t). \end{aligned} \tag{14}$$

Using the forms of (14), expressions (10), (11), (12) and (13) give

$$\frac{d^2u_0}{dy^2}+\frac{du_0}{dy}-M_1u_0=-Gr\theta_0-Gm\phi_0\ , \tag{15}$$

$$\lambda\frac{d^2\theta_0}{dy^2}+\Pr\frac{d\theta_0}{dy}-i\omega\Pr\theta_0=-N_r\phi, \tag{16}$$

$$\frac{d^2\phi_0}{dy^2}+Sc\frac{d\phi_0}{dy}-M_2\phi_0=0, \tag{17}$$

where

$$M_1=\frac{1}{K}+i\omega\ ,\ M_2=F+i\omega \text{ (say)}.$$

With initio – boundary conditions as:

$$\begin{aligned} &u_0=0, \theta_0=0,\ \phi_0=0\ , \text{ for every } y \text{ when } t\le 0. \\ &u_0=1,\ \theta_0=1,\ \phi_0=1 \text{ at } y=0 \text{ when } t>0, \\ &u_0\to 0, \theta_0\to 0, \phi_0\to 0, \text{ for } y\to\infty, \text{ when } t>0. \end{aligned} \tag{18}$$

The real part of expressions for non-dimensional concentration, temperature and velocity of fluid particles in the boundary layer are thus finally calculated and expressed in closed form as:

$$\phi_R(y,t) = \exp(-a_1 y)\cos(\omega t - b_1 y) \ , \tag{19}$$

$$\theta_R(y,t) = (c_1 e\,\mathrm{xp}(-a_1 y) + d_1 e\,\mathrm{xp}(-a_2 y))\cos(\omega t) - (c_2 e\,\mathrm{xp}(-a_1 y) + d_2 e\,\mathrm{xp}(-a_2 y))\sin(\omega t), \tag{20}$$

$$u_R(y,t) = (e_5 \exp(-a_1 y) + e_7 \exp(-a_2 y))\cos(\omega t) - (e_6 \exp(-a_1 y) + e_8 \exp(-a_2 y))\sin(\omega t) + e_9 \exp(-a_3 y)\cos(\omega t - b_3 y) - e_{10} \exp(-a_3 y)\sin(\omega t - b_3 y). \tag{21}$$

Skin- friction at the plate:

The real part of the non-dimensional skin-friction co-efficient at the plate is obtained as:

$$\tau_R = \left(\frac{\partial u_R}{\partial y}\right)_{y=0} = \tau_a \cos(\omega t) + \tau_b \sin(\omega t) \ . \tag{22}$$

Rate of heat transfer coefficient:

The real part of the rate of heat transfer co-efficient in terms of the Nusselt number is given as,

$$Nu_R = -\frac{1}{Pr}\left(\frac{\partial \theta_R}{\partial y}\right)_{y=0} = Nu_1\, cos(\omega t) + Nu_2 \sin(\omega t) \, . \tag{23}$$

Rate of mass transfer coefficient:

The real part of the rate of mass transfer co-efficient in terms of the Sherwood number is

$$Sh_R = -\frac{1}{Sc}\left(\frac{\partial \phi_R}{\partial y}\right)_{y=0} = a_1 \cos(\omega t) - b_1 \sin(\omega t) \, . \tag{24}$$

4. Results and discussion

The present paper deals with the problem of a two- dimensional unsteady flow of a viscous chemically absorption fluid past an impulsively accelerated plate embedded in porous media with thermal radiation, first order chemical reaction and oscillating plate temperature and concentrations. Numerical results for the velocity temperature and concentration functions with friction co-efficient, rate of heat and mass transfer are calculated using a normal mode method for different values of the parameters such as *Pr*, *Gr*, *Gm*, *Sr*, *Sc*, *F*, *R*, *K*, u_0, ω, y and t. In the present study we have chosen fixed values for K =0.5, ω=0.05 and u_0=1.0, while the other parametric values are varied over a range and are specified in respective legends. In this study, water is taken as a primary fluid (solvent), whose Prandtl number (*Pr*) is as 7.0 at 25^0 C or $298K$ and 1 atmosphere of pressure. To produce a substantial effect on mass diffusion, some fluids considered as secondary (solute) such as Helium (*He)*, Water vapor (H_2O), Ammonia (NH_3) and Carbon dioxide (CO_2) are diffused through the air. The Schmidt number (*Sc*) of the corresponding secondary species are taken as respectively as 0.30, 0.60, 0.78, 0.98 and the Prandtl number of the diffused fluids are all considered as 7.0.

In Figure 2, the parametric effect of the first order chemical reaction (*F*) on the non-dimensional concentration ϕ_R against the normal distance y is presented. It is found that as the value of *F* increases, the concentration of the fluid particles near the plate decreases. Due to the presence of *F*, the mass diffusivity decreases, and this results in a reduction of the thickness of the concentration boundary layer and ultimately the value of ϕ_R. The influence of various parameters like the thermal radiation (*R*), and the radiation absorption (N_r) on the non-dimensional temperature θ_R is depicted in figures 3 and 4. The increase in both *R* and N_r affect the growth of the thermal boundary layer and thereby increase the value of θ_R

.

Figures 5, 6 and 7 present graphically the way in which the flow rate is regulated by the influence of the chemical reaction parameter (*F*), the radiation absorption parameter (N_r) and the permeability parameter (*K*) against the normal distance y. Due to an increase in values of *F*, the fluid velocity is found decreasing, while a reverse phenomenon is observed for an increase in the values of N_r and *K*. An increase in the value of *F* decreases the concentration near the plate, which results in decreasing the mass buoyancy force and thus decreasing the value of u_R. On the other hand due to an increase in the value of N_r, the temperature near the plate increases, which helps to increase the kinetic energy of the fluid particles and thus increases the flow rate and the values of u_R. As the value of *K* increases, the drag force decreases causing increases the flow rate and the value of the velocity u_R. It is interesting to observe that, the velocity profile attains its maximum peak near the plate, which is found to died out away from the plate; this is in parity with the fact that, the effect of the buoyancy forces near the plate is more than at a distance far away from the plate.

Figure 8 depicts the effect of the chemical reaction parameter (*F*) on the rate of mass transfer quantified as the Sherwood number (Sh_R) against time *t*. An increase in the values of *F* encourages in transporting masses very near to the plate surface (a higher concentration zone) to the fluid region (a lower concentration zone) thereby increasing the phenomena of mass transfer and the Sherwood number (Sh_R), while the rate of mass transfer is gradually decrease as time propagates.

The influence of thermal radiation parameter (*R*) and chemical reaction parameter (*F*) on the heat transfer rate quantified by Nusselt number (Nu_R) against radiation absorption parameter (N_r) is shown graphically in figures 9 and 10. It is observed that, an increase in values of *F*, accelerate the rate of heat transfer from near the plate surface towards far away from the plate surface, while it is found to decelerate due to increase in values of *R* and N_r.

Table 1 reflects numerically the physical influence of the thermal radiation parameter (*R*) on the rate of flow against the normal distance y. It is clearly seen that, the flow rate accelerate due to an increase in values of *R* but decelerate gradually far away from the plate as y ϵ (0, 7]. As expected in free convective flow, the rate of flow and thus the value of u_R increase due to increases in the thermal buoyancy forces affected by an increase in the temperature near the plate. The effect of chemical reaction (*F*) and thermal radiation (*R*) on the skin-friction τ_R against radiation absorption parameter (N_r) have been depicted numerically through Tables 2 and 3. These tables clearly show that, the skin-friction τ_R increases incredibly with increase in the values of N_r. But, due to an increase in the values of *F*, the skin –frictional effect is found to be decreasing, while for $0 \leq N_r \leq 1.5$, the values of τ_R is seen decreasing up to $R = 2.25$ and then start increasing for $R \geq 3.0$. Whereas τ_R is found decreasing uniformly due to increase in values of *R* against $N_r \geq 2.0$.

5. Conclusions

An unsteady two-dimensional free convective flow of a Newtonian incompressible viscous fluid through a suddenly accelerated vertical plate immersed in Darcian porous media in the presence of thermal radiation and first order chemical reaction with radiation absorption effect is considered for study. The plate temperatures as well as the concentrations of the fluid particles adherent to the plate are supposed to oscillate suddenly in an exponential order. The system of partial differential equations generated from the physical situation is transformed to a set of ordinary differential equations by using a set of transformations and are solved in exact closed form. The outcome of the study can be concluded as:

- The presence of Chemical reaction parameter decreases the concentration near the plate, while the Sherwood number is seen to increase by any increase of the chemical reaction parameter. So, the presence of a chemical reaction parameter plays a significant role in transferring the masses from the solid boundary.

- The temperature profiles increase with an increase in the values of the thermal radiation and absorption parameters.

- The chemical reaction parameter is seen to decrease the velocity of the fluid particles, whereas the fluid velocity is found increasing due to an increase in the radiation absorption and permeability parameters.

- The Nusselt number increases with an increase in the values of the chemical reaction parameter, while the Nusselt number decreases due to an increase in the thermal radiation and absorption parameters.

- The influence of radiation absorption is to increase the skin-friction to an appreciable amount and the skin-friction is found decreasing with increases in the thermal radiation and chemical reaction parameters.

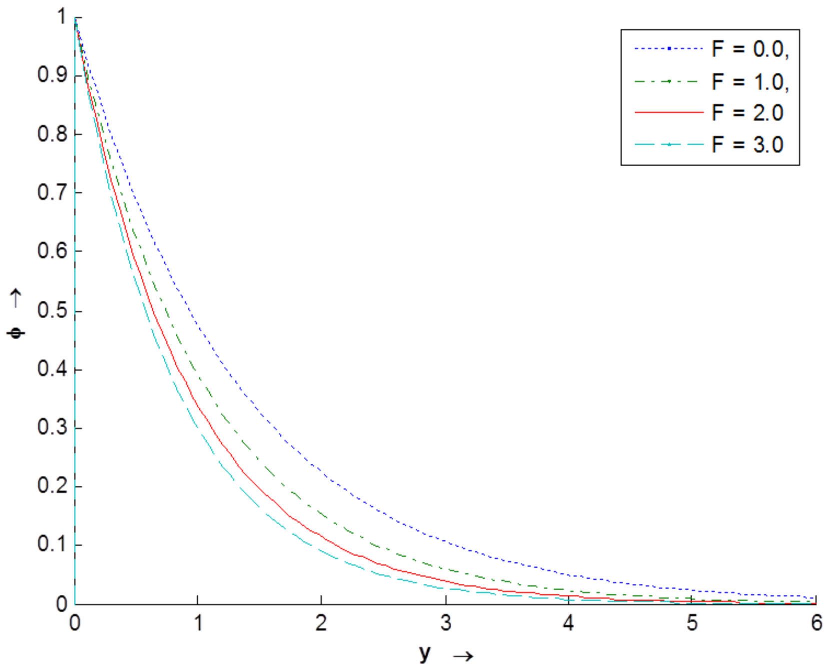

Figure 2. Graph showing variation of chemical reaction (F) on real part of concentration against normal distance for fixed values of Sc = 0.78, ω = 0.2, t = 0.1

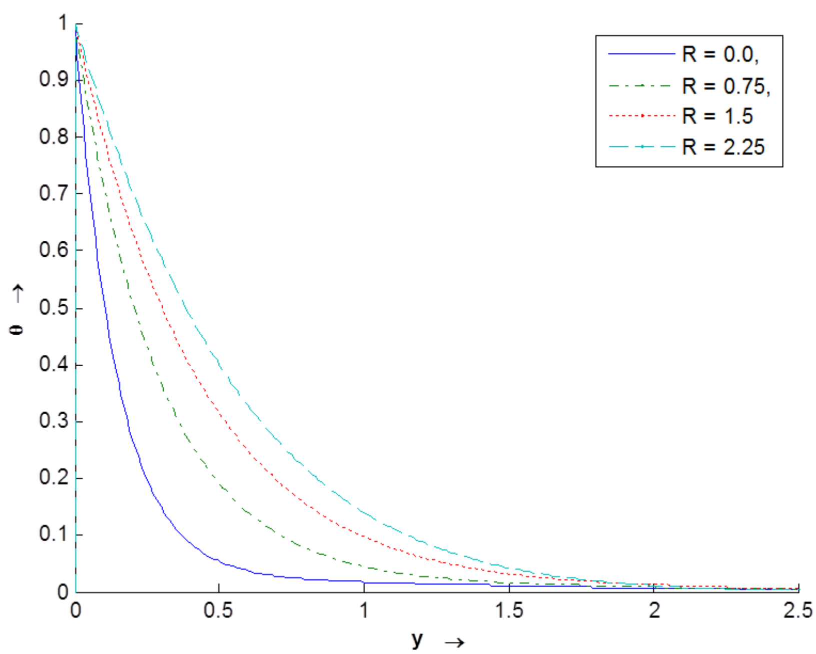

Figure 3. Graph showing variation of thermal radiation (R) on real part of temperature against normal distance for fixed values of F=0.2, ω =0.2, t=0.1, Sc=0.78, N_r =0.2, Pr=7.0

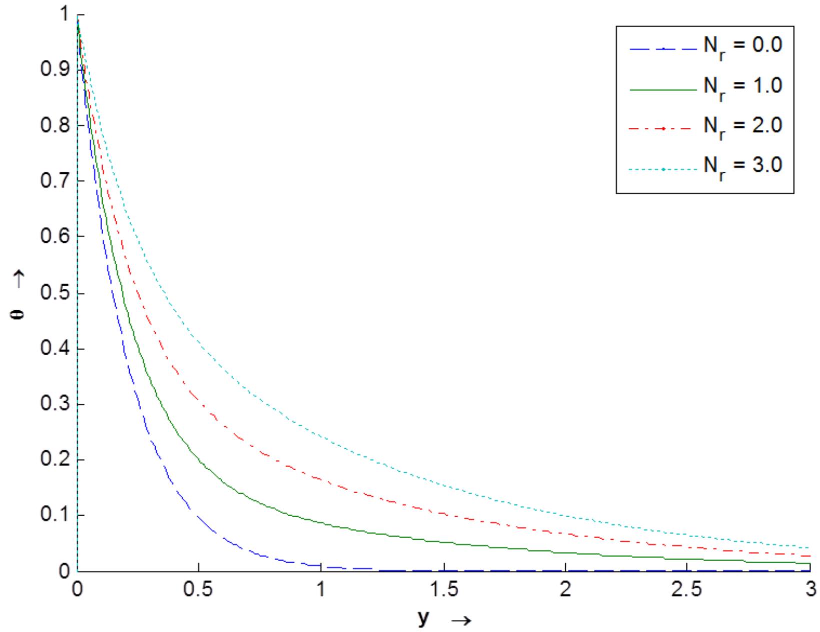

Figure 4. Graph showing variation of absorption parameter (N_r) on real part of temperature against *y* for fixed values of *F*=0.2, ω =0.2, *t*=0.1, *Sc*=0.78, *R*=0.375, *Pr*=7.0

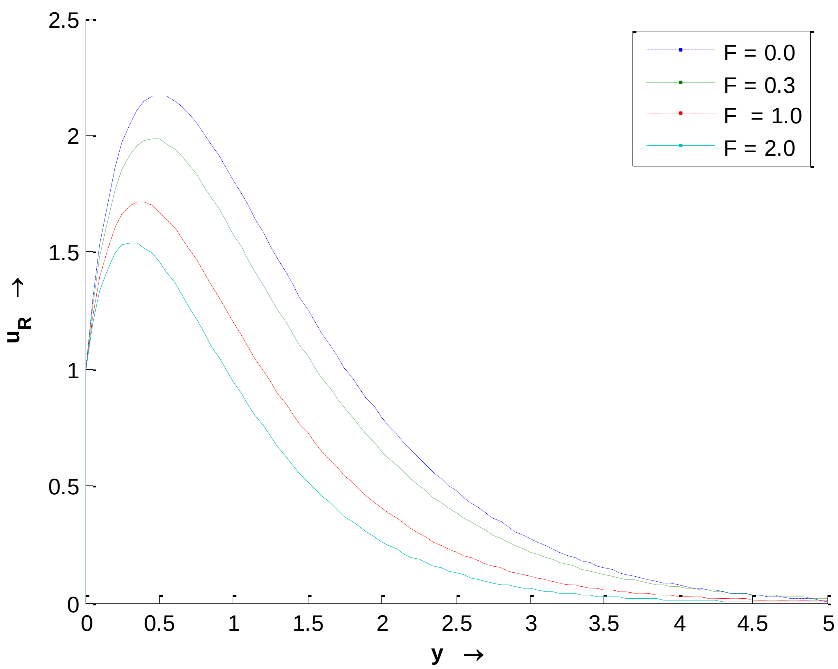

Figure 5. Graph showing variation of chemical reaction parameter (*F*) on real part of velocity against normal distances for fixed *Pr*=7.0, ω =0.3, *t* =0.1, *Sc*=0.78, *R*=0.15, *Gr*=15, *Gm*=10, *K*=0.5, N_r =0.2, $u_0 = 1.0$

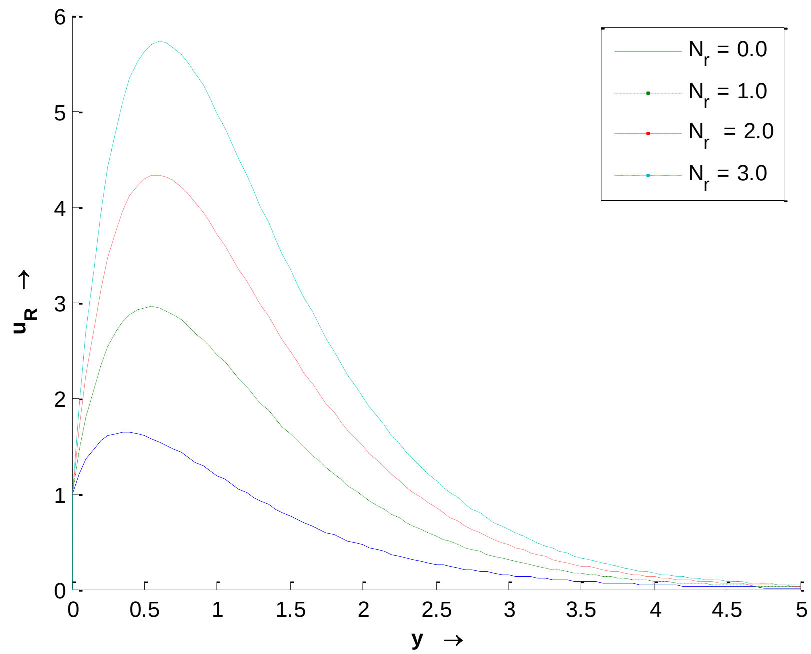

Figure 6. Graph showing variation of absorption parameter (N_r) on real part of velocity against y for fixed F=0.5, ω =0.3, t=0.1, Sc=0.78, Pr=7.0, Gr=15, Gm=10, K=0.5, R=0.15, $u_0 = 1.0$

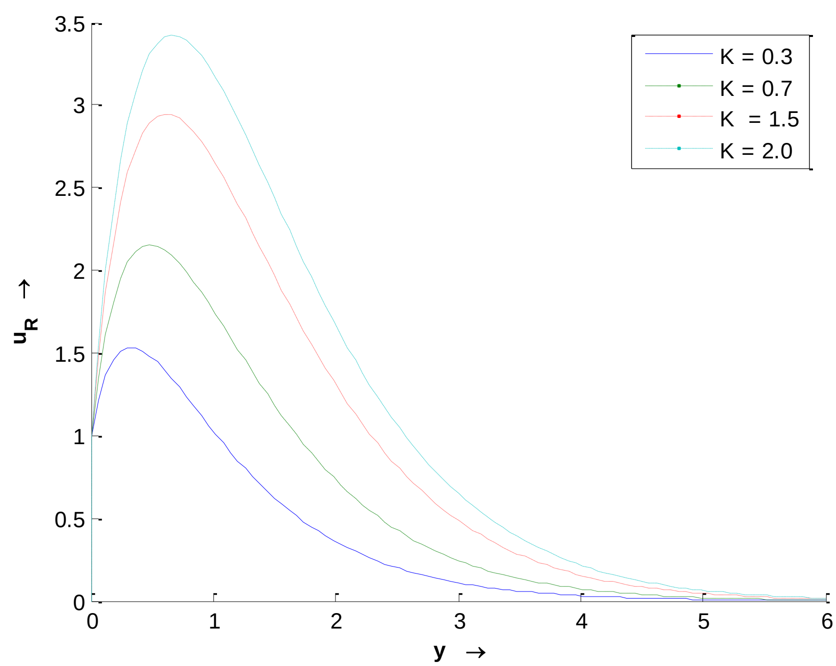

Figure 7. Graph showing variation of permeability parameter (K) on real part of velocity against y for fixed F=0.5, N_r =0.2, ω =0.3, t=0.1, Sc=0.78, Pr=7.0, Gr=15, Gm=10, R=0.15, $u_0 = 1.0$

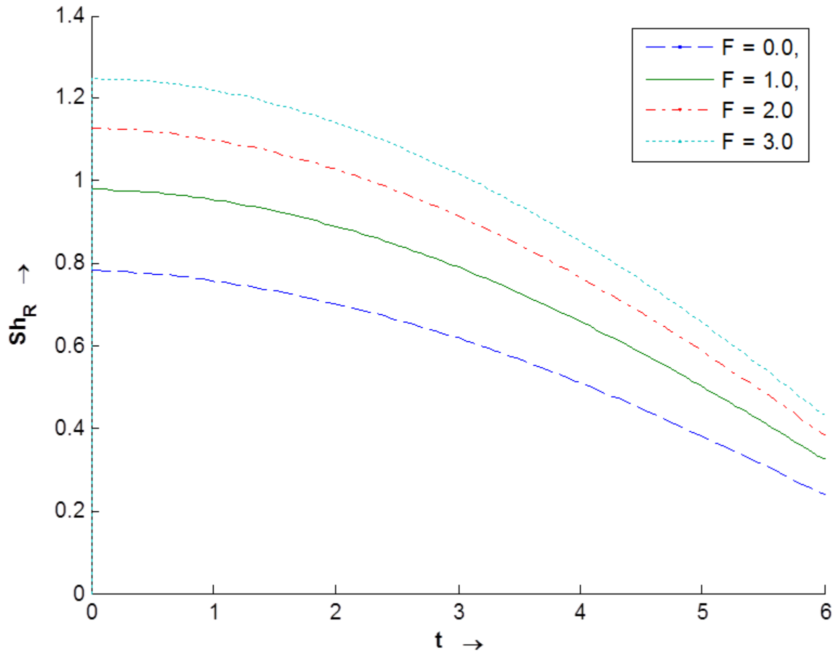

Figure 8. Graph showing variation of chemical reaction parameter (F) on real part of Sherwood number against normal distance for fixed Sc=0.78, ω =0.2

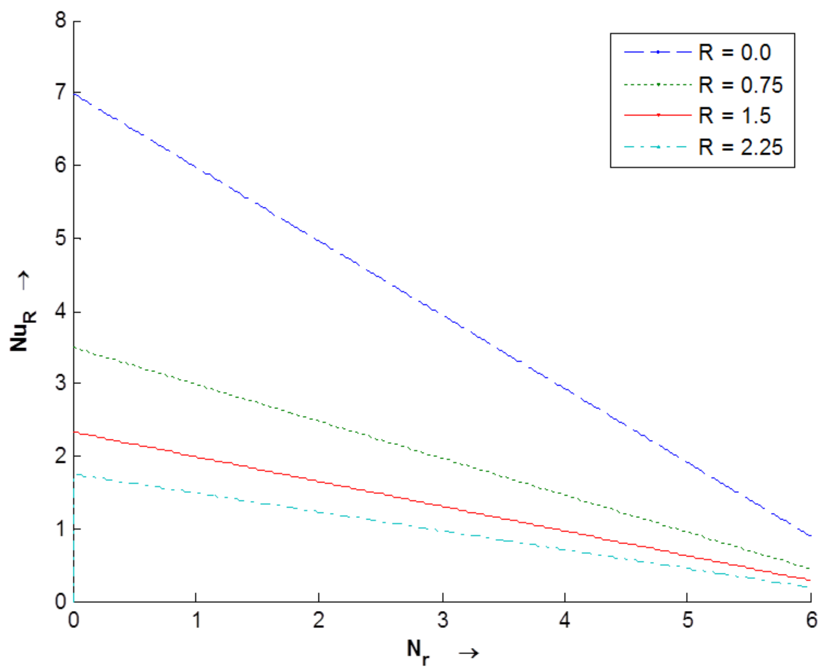

Figure 9. Graph showing variation of radiation parameter (R) on real part of Nusselt number against N_r for fixed F=1.0, ω =0.05, t=0.1, Sc=0.78, Pr=7.0

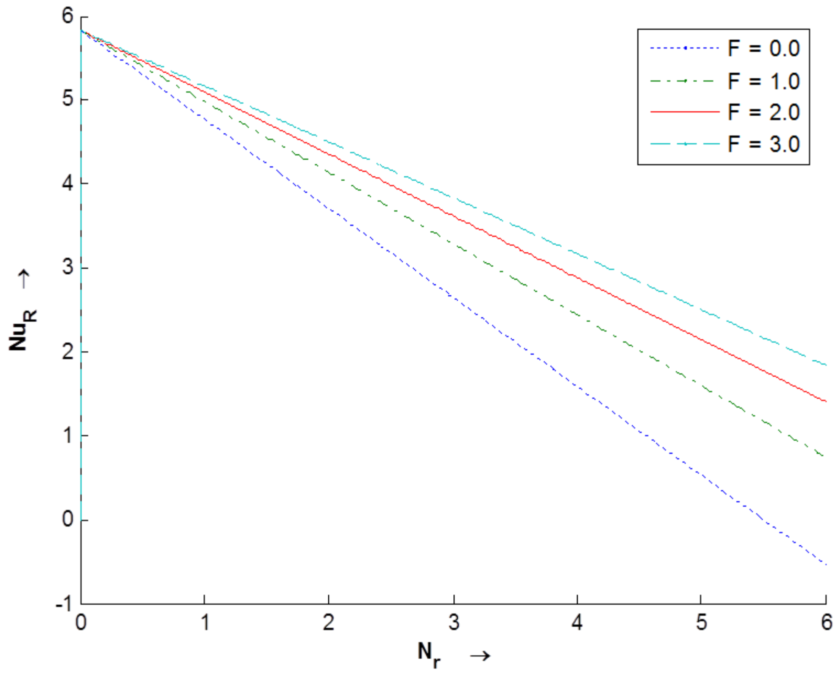

Figure 10. Graph showing variation of chemical reaction parameter (F) on real part of Nusselt number against absorption parameter for fixed R=0.15, ω =0.05, t=0.1, Sc=0.78, Pr=7.0

Table 1. Table showing numerical values of velocity u_R for different values of thermal radiation parameter (R) against arbitrary values of y and for fixed values of Pr =7.0, Sc=0.78, t=0.1, Gr=15.0, Gm=10.0, F=0.5, Q=0.2, K=0.5, $u_0 = 1.0$ ω=0.05

y	R= 0.0	R = 0.75	R = 1.5	R= 2.25
0.0	1.0000	1.0000	1.0000	1.0000
0.7	1.7892	2.0655	2.3965	2.7091
1.4	1.1096	1.2376	1.4470	1.7030
2.1	0.5765	0.6270	0.7217	0.8649
2.8	0.2795	0.2998	0.3388	0.4077
3.5	0.1312	0.1397	0.1556	0.1865
4.2	0.0605	0.0642	0.0708	0.0843
4.9	0.0277	0.0293	0.0321	0.0379
5.6	0.0126	0.0133	0.0146	0.0171
6.3	0.0057	0.0061	0.0066	0.0077
7.0	0.0027	0.0027	0.0030	0.0035

Table 2. Table showing numerical values of skin-friction τ_R for different values of chemical reaction parameter (F) against arbitrary values of N_r and for fixed values of *Pr* =7.0, *Sc*=0.78, *t*=0.1, *R*=0.15, *Gr*=15.0, *Gm*=10.0, *K*=0.5, $u_0 = 1.0$ ω=0.05

N_r	*F*= 0.0	*F* = 0.5	*F* = 1.0	*F* = 2.0
0.0	5.8111	5.4859	5.2467	4.8974
0.5	8.5995	8.0757	7.7368	7.3265
1.0	11.3880	10.6655	10.2269	9.7556
1.5	14.1764	13.2553	12.7169	12.1848
2.0	16.9649	15.8452	15.2070	14.6139
2.5	19.7533	18.4350	17.6971	17.0431
3.0	22.5417	21.0284	20.1872	19.4722
3.5	25.3302	23.6146	22.6773	21.9013
4.0	28.1186	26.2044	25.1674	24.3305
4.5	30.9071	28.7943	27.6575	26.7596
5.0	33.6955	31.3841	30.1476	29.1888

Table 3. Table showing numerical values of skin-friction τ_R for different values of thermal radiation parameter (R) against arbitrary values of N_r and for fixed values of *Pr* =7.0, *Sc*=0.78, *t*=0.1, *F*=1.0, *Gr*=15.0, *Gm*=10.0, *K*=0.5, $u_0 = 1.0$ ω=0.05

N_r	*R= 0.0*	*R= 0.75*	*R = 2.25*	*R = 3.0*
0.0	5.1663	6.6072	6.9244	8.8536
0.5	8.4444	7.7653	6.6789	8.0226
1.0	11.7225	8.9234	6.4334	7.1917
1.5	15.0006	10.0815	6. 1879	6.3607
2.0	18.2787	11.2396	5.9425	5.5297
2.5	21.5568	12.3977	5.6970	4.6987
3.0	24.8349	13.5558	5.4515	3.8677
3.5	28.1131	14.7139	5.2060	3.0367
4.0	31.3912	15.8720	4.9605	2.2058
4.5	34.6693	17.0301	4.7151	1.3748
5.0	37.9474	18.1882	4 .4696	0.5438

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REFERENCES

Ahmed, N., Sengupta, S. and Datta, D. (2013). An exact analysis for MHD free convection mass transfer flow past an oscillating plate embedded in a porous medium with Soret effect, Chem. Eng. Comm., 200, pp.494–513.

Astarita, G. (1967). Mass transfer with chemical reaction, Elsevier Publishing Company, Amsterdam.

Bejan, A. (1987). Convective heat transfer in porous media. J. Willey & Sons, New York.

Cess, R.D. (1966). The interaction of thermal radiation with free convection heat transfer, International Journal of heat and mass transfer, 9, pp.1269-1277.

Hossain, M.A., Takhar, H.S. (1996). Radiation effect on mixed convection along a vertical plate with uniform surface temperature. Heat Mass Transfer, 31, pp. 243–248.

Jaiswal, B. S. and Soundalgekar, V. M. (2001). Oscillating plate temperature effects on a flow past an infinite vertical porous plate with constant suction and embedded in a porous medium, Heat and Mass Transfer, 37, pp.125–131.

Jang, J.Y. and Ni, J.R. (1989). Transient free convection with mass transfer from an isothermal vertical plate embedded in a porous medium, Int. J. Heat and Fluid Flow, 10, pp. 59–85.

Kandasamy, R., Periasamy, K., Sivagnana, P. K.K. (2006). Effects of chemical reaction, heat and mass transfer along a wedge with heat source and concentration in the presence of suction or injection. Int J Heat Mass Transfer, 48(7), pp. 1388–1394.

Kim, S.J. and Vafai, K. (1989). Analysis of natural convection about a vertical plate embedded in a porous medium, Int. J. Heat Mass Transfer, 32, pp. 665–677.

Makinde, O.D. (2009). On MHD boundary layer flow and mass transfer past a vertical plate in a porous medium with constant heat flux. Int J Numer Meth Heat Fluid Flow, 19, pp.546–54.

Makinde, O. D., Olanrewaju P. O. and Charles, W.M. (2011). Unsteady convection with chemical reaction and radiative heat transfer past a porous plate moving through a binary mixture, Afrika Matematika A.M, 21, pp. 1 – 17.

Muthucumaraswamy, R. and Ganesan, P. (1998). Unsteady flow past an impulsively started vertical plate with heat and mass transfer, Heat Mass Transfer, 34, pp. 187–193.

Muthucumaraswamy, R. and Ganesan, P. (1999). Flow past an impulsively started vertical plate with variable temperature and mass flux, Heat Mass Transfer, pp. 487–493.

Muthukumarswamy, R., Ganeshan, P. and Soundalgekar, V.M. (2001). Heat and mass transfer effects on flow past an impulsively started vertical plate, Acta Mech.,146, pp.1-8.

Oahimire, J.I., Olajuwon, B. I. (2014). Effects of radiation absorption and thermo-diffusion on MHD heat and mass transfer flow of a micro-polar fluid in the presence of heat Source, Applications and Applied mathematics, 9(2), pp. 763-779.

Pathak, G., Maheshwari, C.H and Gupta, S.P. (2006). Effect of radiation on unsteady free convection flow bounded by an oscillating platewith variable wall temperature**,** Int. J. of Applied Mechanics and Engineering, 11(2), pp.371-382.

Raptis, A., Singh, A.K. (1985). Free convection flow past an impulsively started vertical plate in a porous medium by finite difference method, Astrophys. Space Sci., 112, pp. 259–265.

Seddeek, M. A. and Almushigeh, A. A. (2010). Effects of radiation and variable viscosity on MHD free convective flow and mass transfer over a stretching sheet with chemical reaction, Applications and Applied mathematics, 5 (1), pp. 181-7197.

Seddeek, M.A, Darwish, A.A and Abdelmeguid, M.S. (2007). Effects of chemical reaction and variable viscosity on hydromagnetic mixed convection heat and mass transfer for Hiemenz flow through porous media with radiation. Commun Nonlinear Sci Numer Simul., 12, pp. 195–213.
Sengupta, Sanjib (2011). Thermal diffusion effect of free convection mass transfer flow past a uniformly accelerated porous plate with heat sink, International Journal of Mathematical Archive, 2, pp. 1266-1273.
Sengupta, Sanjib (2012). Radiative mixed convection mass transfer flow past an iso-thermal porous plate embedded in a permeable medium in presence of thermal diffusion and heat generation, International Journal of Computer Applications, 40, pp. 17-22.
Soundalgekar, V.M. (1977). Free convection effects on the Stokes problem for infinite vertical plate, ASME J. Heat Transfer, pp. 499–501.
Soundalgekar, V.M. (1979). Effects of mass transfer and free convection on the flow past an impulsively started vertical plate, ASME J. Appl. Mech., 46, pp. 757–760.
Sudheer Babu, M. and Satyanarayana, P.V. (2009). Effects of the chemical reaction and radiation absorption on free convection flow through porous medium with variable suction in the presence of uniform magnetic field, J.P. Journal of Heat and Mass Transfer, 3, pp. 219-234.
Takhar, H.S, Chamkha, A. J and Nath, G. (2000). Flow and mass transfer on a stretching sheet with a magnetic field and chemically reactive species. Int J Eng Sci., 38, pp. 1303–1314.
Takhar, H.S. and Sondalgekar, V.M. (1991). Free Convection Heat and Mass Transfer in a Porous Medium, Convective heat and mass transfer in porous media, 196, pp. 123-142.
Vafai, K. and Tien, C.L. (1981). Boundary and inertia effects on flow and heat transfer in porous media, Int. J. Heat Mass Transfer, 24, pp. 195–203.

APPENDIXE

$$a_1 = \frac{1}{2}\left[Sc + \frac{\sqrt{Sc}}{\sqrt{2}}\sqrt{\left((Sc+4F)+\sqrt{(Sc+4F)^2+16\omega^2}\right)}\right],$$

$$b_1 = \frac{\sqrt{Sc}}{2\sqrt{2}}\sqrt{\left(\sqrt{((Sc+4F)^2+16\omega^2}-(Sc+4F)\right)}$$

$$x_1 = \lambda(a_1{}^2 - b_1{}^2) - \Pr a_1, \; x_2 = 2a_1b_1\lambda - \Pr b_1 - \omega\Pr,$$

$$c_1(y) = -\frac{N_r \Pr}{x_1{}^2 + x_2{}^2}(x_1\cos(\beta_1 y) - x_2\sin(\beta_1 y)),$$

$$c_2(y) = \frac{N_r \Pr}{x_1{}^2 + x_2{}^2}(x_2\cos(\beta_1 y) + x_1\sin(\beta_1 y)),$$

$$a_2 = \frac{1}{2\lambda}\left[\Pr + \frac{\sqrt{\Pr}}{\sqrt{2}}\sqrt{\left(\Pr+\sqrt{\Pr^2+16\omega^2\lambda^2}\right)}\right],$$

$$b_2 = \frac{\sqrt{\Pr}}{2\lambda\sqrt{2}}\sqrt{\left(\sqrt{\Pr^2+16\omega^2\lambda^2}-\Pr\right)} \quad x_3 = a_2{}^2 - b_2{}^2 - a_2 - \frac{u_0}{K},$$

$$x_4 = 2a_2b_2 - b_2 - \omega u_0 \,, d_1 = (1-c_1)\cos(b_2 y) - c_2 \sin(b_2 y) \,,$$
$$d_2 = c_2 \cos(b_2 y) + (1-c_1)\sin(b_2 y) \,,$$
$$e_1(y) = -\frac{Gr}{x_3^{\,2} + x_4^{\,2}}(x_3 \cos(\beta_2 y) - x_4 \sin(\beta_2 y)) \,,$$
$$e_2(y) = \frac{Gr}{x_3^{\,2} + x_4^{\,2}}(x_4 \cos(\beta_2 y) + x_3 \sin(\beta_2 y)) \,,$$
$$x_5 = a_2^{\,2} - (b_1 + b_2)^2 - a_2 - \frac{u_0}{K} \,,$$
$$x_6 = 2a_2(b_1 + b_2) - (b_1 + b_2) - \omega u_0 \,,$$
$$y_1(y) = x_5 \cos(\beta_1 + \beta_2) y - x_6 \sin(\beta_1 + \beta_2) y \,,$$
$$y_2(y) = x_6 \cos(\beta_1 + \beta_2) y + x_5 \sin(\beta_1 + \beta_2) y \,,$$
$$e_3(y) = -\frac{GrN_r \Pr(x_1 y_1 - x_2 y_2)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \,, e_4(y) = \frac{GrN_r \Pr(x_1 y_2 + x_2 y_1)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \,,$$
$$x_7 = a_1^{\,2} - b_1^{\,2} - a_1 - \frac{u_0}{K} \,, x_8 = 2a_1b_1 - b_1 - \omega u_0 \,,$$
$$y_3 = \mathrm{x}_7 \cos(\mathrm{b}_1 \mathrm{y}) - \mathrm{x}_8 \sin(\mathrm{b}_1 \mathrm{y}) \,, y_4 = \mathrm{x}_8 \cos(\mathrm{b}_1 \mathrm{y}) + \mathrm{x}_7 \sin(\mathrm{b}_1 \mathrm{y}) \,.$$
$$e_5(y) = \frac{GrN_r \Pr(x_1 y_3 - x_2 y_4)}{(x_1^{\,2} + x_2^{\,2})(x_7^{\,2} + x_8^{\,2})} \,, e_5(y) = -\frac{GrN_r \Pr(x_1 y_4 + x_2 y_3)}{(x_1^{\,2} + x_2^{\,2})(x_7^{\,2} + x_8^{\,2})} \,,$$
$$e_7(y) = -\frac{Gm(x_7 \cos(b_1 y) - x_8 \sin(b_1 y))}{x_7^{\,2} + x_8^{\,2}} \,, e_8(y) = \frac{Gm(x_8 \cos(b_1 y) + x_7 \sin(b_1 y))}{x_7^{\,2} + x_8^{\,2}} \,,$$
$$e_9(y) = e_5 + e_7 \,, e_{10}(y) = e_6 + e_8 \,, \; e_{11}(y) = e_1 + e_3 \,,$$
$$e_{12}(y) = e_2 + e_4 \,, \; \tau_{a1}(y) = \frac{Gm(a_1 x_7 + b_1 x_8)}{x_7^{\,2} + x_8^{\,2}} \,,$$
$$\tau_{b1}(y) = \frac{Gm(a_1 x_8 - b_1 x_7)}{x_7^{\,2} + x_8^{\,2}} \,, \tau_{a2}(y) = \frac{a_2 x_3 Gr}{x_3^{\,2} + x_4^{\,2}} + \frac{a_2 N_r Gr(x_1 x_5 - x_2 x_6)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \,,$$
$$\tau_{b2}(y) = \frac{a_2 x_4 Gr}{x_3^{\,2} + x_4^{\,2}} + \frac{a_2 N_r Gr(x_1 x_6 + x_2 x_5)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \; \tau_{a3}(y) = \frac{b_2 x_4 Gr}{x_3^{\,2} + x_4^{\,2}} + \frac{(b_1 + b_2) N_r Gr(x_1 x_6 + x_2 x_5)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \,,$$
$$\tau_{b3}(y) = -\frac{b_2 x_3 Gr}{x_3^{\,2} + x_4^{\,2}} - \frac{(b_1 + b_2) N_r Gr(x_1 x_5 + x_2 x_6)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \,,$$
$$\tau_{a4}(y) = -a_3 \left(1 + \frac{x_7 Gm}{x_7^{\,2} + x_8^{\,2}} + \frac{x_3 Gr}{x_3^{\,2} + x_4^{\,2}} + \frac{N_r Gr(x_1 x_5 - x_2 x_6)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \right),$$
$$\tau_{b4}(y) = -a_3 \left(\frac{x_4 Gr}{x_3^{\,2} + x_4^{\,2}} + \frac{x_8 Gm}{x_7^{\,2} + x_8^{\,2}} + \frac{N_r Gr(x_1 x_6 + x_2 x_5)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \right),$$
$$\tau_{a5}(y) = -b_3 \left(\frac{x_4 Gr}{x_3^{\,2} + x_4^{\,2}} + \frac{x_8 Gm}{x_7^{\,2} + x_8^{\,2}} + \frac{N_r Gr(x_1 x_6 + x_2 x_5)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \right),$$
$$\tau_{b5}(y) = -b_3 \left(1 + \frac{x_3 Gr}{x_3^{\,2} + x_4^{\,2}} + \frac{x_7 Gm}{x_7^{\,2} + x_8^{\,2}} + \frac{N_r Gr(x_1 x_5 - x_2 x_6)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \right),$$
$$\tau_{a6}(y) = -\frac{x_4 b_2 Gr}{x_3^{\,2} + x_4^{\,2}} - \frac{x_8 b_1 Gm}{x_7^{\,2} + x_8^{\,2}} + \frac{N_r Gr(x_1 x_6 + x_2 x_6)(b_1 + b_2)}{(x_1^{\,2} + x_2^{\,2})(x_5^{\,2} + x_6^{\,2})} \,,$$

$$\tau_{b6}(y)=\frac{x_3 b_2 Gr}{x_3^{\;2}+x_4^{\;2}}+\frac{x_7 b_1 Gm}{x_7^{\;2}+x_8^{\;2}}+\frac{N_r Gr(x_1x_5-x_2x_6)(b_1+b_2)}{(x_1^{\;2}+x_2^{\;2})(x_5^{\;2}+x_6^{\;2})},$$

$$\tau_a=\tau_{a1}+\tau_{a2}+\tau_{a3}+\tau_{a4}+\tau_{a5}+\tau_{a6},\ \tau_b=\tau_{b1}+\tau_{b2}+\tau_{b3}+\tau_{b4}+\tau_{b5}+\tau_{b6}$$

$$Nu_1(y)=-\frac{x_2 b_1 N_r}{x_1^{\;2}+x_2^{\;2}}+\frac{x_2(b_1+b_2)N_r}{x_1^{\;2}+x_2^{\;2}}-\frac{x_1 a_1 N_r}{x_1^{\;2}+x_2^{\;2}}+a_2\left(1+\frac{x_1 N_r}{x_1^{\;2}+x_2^{\;2}}\right),$$

$$Nu_2(y)=-\frac{x_1 b_1 N_r}{x_1^{\;2}+x_2^{\;2}}+\frac{x_1(b_1+b_2)N_r}{x_1^{\;2}+x_2^{\;2}}-\frac{x_2 a_1 N_r}{x_1^{\;2}+x_2^{\;2}}-\frac{x_2 a_2 N_r}{x_1^{\;2}+x_2^{\;2}}+b_2\cdot$$