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A study on free convective heat and mass transfer flow through a highly porous medium with radiation, chemical reaction and Soret effects

K. Suneetha[a], S. Mohammed Ibrahim[b,]* and G. V. Ramana Reddy[c]

[a]*Research Scholar, Department of Mathematics, K. L University Vaddeswaram, Guntur (Dt), 502522, India*
[b]*Department of Mathematics, GITAM University, Visakhapatnam, Andhra Pradesh- 530045, India*
[c]*Department of Mathematics, K L University Vaddeswaram, Guntur (Dt), 502522, India*

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Abstract

This paper addresses the effects of Soret on unsteady free convection flow of viscous incompressible fluid through a porous medium with high porosity bounded by a vertical infinite moving plate under the influence of thermal radiation, chemical reaction, and heat source. The fluid is considered to be gray, absorbing, and emitting but non-scattering medium. Rosseland approximation is considered to describe the radiative heat flux in the energy equation. The dimensionless governing equations for this investigation are solved analytically using perturbation technique. The effects of various governing parameters on the velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number are shown in figures and tables and analyzed in detail. It was noticed that velocity distribution increased with increasing buoyancy parameters; temperature decreased with increasing Prandtl number, and concentration decreased with increasing the Schmidt number and chemical reaction parameter.

1. Introduction

Convective heat and mass transfer in porous media has been a subject of great interest for the last few decades. This interest was motivated by numerous thermal engineering applications in various disciplines, such as geophysical, thermal and insulation engineering, modelling of packed sphere beds, the cooling of electronic systems, chemical catalytic reactors, ceramic processes, grain storage devices fibre and granular insulation, petroleum reservoirs, coal combustors, groundwater pollution and filtration processes. Raptis [1] proposed the presence of a magnetic field through a porous medium. Natural convection from an isothermal vertical surface embedded in a thermally stratified high-porosity medium was investigated by Chen and Lin [2]. Hayat et al. [3] presented the heat and mass transfer and slip flow of a second-grade fluid past a stretching sheet through a porous space. Sreevani [4] presented the heat and mass transfer of mixed convective flow through a porous medium in channels with dissipative effects. Flow with convective acceleration through a porous medium was studied by Yamamoto and lwamura [5].

Corresponding author
email address: ibrahimsvu@gmail.com

Many processes in new engineering areas occur at a high temperature as knowledge of radiative heat and mass transfer become very important for the design of the pertinent equipment. Nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering areas. The study of radiation effects on various types of flows is quite complicated. Makinde [6] analyzed heat and mass transfer and thermal radiation of free convective flow of past a moving vertical porous plate. The presence of radiation and heat and mass transfer flow past a plate was derived by Raptis and Massals [7]. Chamkha et al. [8] presented the effects of radiation on free convection flow past a semi-infinite vertical plate with mass transfer. Prasad et al. [9] investigated the effect of radiation, heat and mass transfer on two dimensional past an impulsively started infinite vertical plate. Free convective flow with the effects of radiation from a porous vertical plate was studied by Hossain et al. [10].

The study of heat generation or absorption in moving fluid is important in problems dealing with dissociating fluids. Possible heat generation effect may alter the temperature distribution; consequently, the particle deposition rate in nuclear reactors, electronic chips and semiconductor wafers. Olanrewaju et al. [11] discovered the effect of internal heat generation and thermal boundary layer with a convective surface boundary condition. Rahman et al. [12] prepared thermo-micropolar fluid flow along a vertical permeable plate with uniform surface heat flux in the presence of heat generation. Radiation effects of heat source/sink and work done by deformation on the flow and heat transfer of a viscoelastic fluid over a stretching sheet were noticed by Bataller [13]. Raptis [14] proposed the effects on heat and mass transfer of free convection flow past an infinite moving vertical porous plate with constant suction and heat source.Hussain et al. [15] derived the effects of radiation on mixed convection along a vertical plate in the presence of heat generation or absorption.

The chemical reaction can be codified as either heterogeneous or homogeneous process. It depends on whether they occur at an interface or as a single phase volume reaction. Sudheer babu and Satya Narayana [16] derived the chemical reaction and radiation absorption effects on free convection flow through a porous medium with variable suction in the presence of a uniform magnetic field. Unsteady Magnetohydrodynamics (MHD) free convection and chemical reaction flow past an infinite vertical porous plate were studied by Raju et al. [17]. Patil and Kullkarni [18] investigated the chemical reaction effect of the free convective flow of a polar fluid through a porous medium in the presence of internal heat generation. Muthukumaraswamy and Ganesan [19] examined diffusion and first-order chemical reaction on impulsively started infinite vertical plate with variable temperature. The analysis of heat and mass transfer, chemical reaction along a wedge with heat source and concentration in the presence of suction or injection was presented by Kandaswamy et al. [20]. Ibrahim [21] examined the effects of chemical reaction and radiation on free convective flow through a highly porous medium under the influence of heat generation.

Soret is the thermal-diffusion effect, for instance, has been utilized for isotope separation and in mixtures between gases with very light molecular weight (H_2, H_e) and of medium molecular weight (N_2, air). Hari Mohan [22] presented the Soret effect on the rotator thermosolutal convection of the Veronis type. Plattern and Charepeyer [23] represented the Soret effect of oscillatory motion in Bernard cell. Soret and chemical reaction effects on magnetohydrodynamic free convective water’s memory flow with constant suction and heat sink were derived by Pavan kumar et al. [24]. David Jacqmin [25] derived parallel flows with Soret effect in tilted cylinders. Hurle and Jakeman [26] presented the significance of the Soret effect in the Rayleigh-Jeffrey’s problem.

Motivated by the above literature and applications, the present paper explores heat and mass transfer by free convection from a vertical infinite moving plate saturated highly porous medium. The problem is in the presence of thermal radiation, heat source, and chemical reaction and has a Soret number. The governing equations are solved analytically using the perturbation method. The results are presented graphically and in tabular form and different physical aspects of the problem have been discussed.

Applications of the study this study is expected to be useful in understanding the influence of heat and mass transfer problems with chemical reaction are of importance in many processes and have, therefore received a considerable amount of attention in recent years. In processes such as drying, evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow in a desert cooler, in chemical reaction engineering heat and mass transfer occur simultaneously.

2. Mathematical analysis

An unsteady two-dimensional laminar free convective mass transfer flow of a viscous incompressible fluid through a highly porous medium past an infinite vertical moving porous plate in the presence of thermal radiation, heat generation, chemical reaction, and Soret is considered. The fluid and porous structure are assumed to be in local thermal equilibrium. It is also assumed that there is radiation only from the fluid [27-29]. The fluid is a gray, emitting, and absorbing, but non-scattering medium, and the Rosseland approximation is used to describe the radiative heat flux in the energy equation. A homogeneous first-order chemical reaction between the fluid and species concentration is considered, in which the rate of chemical reaction is directly proportional to the species concentration. All the fluid properties are assumed to be constant except that the influence of the density variation with temperature is considered only in the body force term (Boussinesq's approximation) [21, 28, 29]. The x^*-axis is chosen along the plate in the direction opposite to the direction of gravity and the y^*-axis is taken normal to it (Fig. 1).

Since the flow field is of extreme size, all the variables are functions of y^* and t^* only. Hence under the usual Boussinesq's approximation, the equations of mass(Eq. (1)), linear momentum (Eq. (2)), energy(Eq. (3)), and diffusion (Eq. (4)) are:

Continuity equation:

$$\frac{\partial v^*}{\partial y^*} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} + \upsilon \frac{\partial^2 u^*}{\partial {y^*}^2} + g\beta\left(T^* - {T_\infty}^*\right) + g\beta^*\left(C^* - {C_\infty}^*\right) - \frac{\upsilon}{k^*}\varphi u^* \tag{2}$$

Energy equation:

$$\sigma \frac{\partial T^*}{\partial t^*} + \varphi v^* \frac{\partial T^*}{\partial y^*} = \frac{k}{\rho C_p}\frac{\partial^2 T^*}{\partial {y^*}^2} - \frac{\varphi}{\rho C_p}\frac{\partial q_r}{\partial y^*} + \frac{Q_0}{\rho C_p}\left(T^* - {T_\infty}^*\right) \tag{3}$$

Diffusion equation:

$$\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial {y^*}^2} - Kr^*\left(C^* - {C_\infty}^*\right) + D_1 \frac{\partial^2 T^*}{\partial {y^*}^2} \tag{4}$$

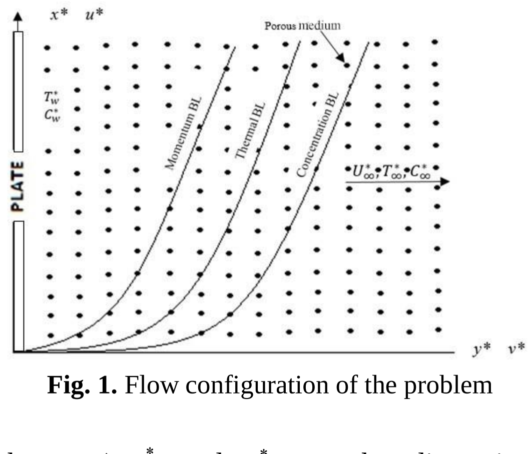

Fig. 1. Flow configuration of the problem

where x^*, y^* and t^* are the dimensional distances along and perpendicular to the plate and dimensional time, respectively; u^*, and v^*

are the components of dimensional velocities along x^* and y^* directions, respectively; C^* and T^* are the dimensional concentration and temperature of the fluid, respectively; ρ is the fluid density; υ is the kinematic viscosity; C_p is the specific heat at constant pressure; σ is the heat capacity ratio; g is the acceleration due to gravity; β and β^* are the volumetric coefficient of thermal and concentration expansion; k^* is the permeability of the porous medium; φ is the porosity; D is the molecular diffusivity; Kr^* is the chemical reaction parameter; *k is* the fluid thermal conductivity, and D_1 is the Soret number . The third and fourth terms on the right-hand side of the momentum (Eq. (2)) denote the thermal and concentration buoyancy effects, respectively, and the fifth term represents the bulk matrix linear resistance, that is, Darcy term. Also, the second term on the right-hand side of the energy (Eq. (3)) represents thermal radiation. The radiative heat flux term by using the Resseland approximation (Brewster [27]) is given by:

$$q_r = \frac{-4\sigma_s}{3k_e}\frac{\partial T^{*4}}{\partial y^*} \tag{5}$$

where σ_s is the Stefan-Boltzman constant and K_e is the men absorption coefficient. It should be noted that by using the Resseland approximation, the present analysis is limited to optically thick fluids. It was assumed that the temperature difference within the flow is sufficiently small such that T^4 may be expressed as a linear function of the temperature. This is accomplished by expanding in a Taylor series about T_∞ and neglecting higher-order terms, thus:

$$T^{*4} \cong 4T_\infty^{*3}T^* - 3T_\infty^{*4} \tag{6}$$

It is assumed that the permeable plate moves with constant velocity in the direction of fluid flow. It is also assumed that the plate temperature and concentration are exponentially varying with time. Under these assumption, the appropriate boundary conditions for the velocity, temperature, and concentration fields are:

$$u^* = U_p^*,\ T^* = T_w^* + \varepsilon(T_w^* - T_\infty^*)e^{n^*t^*},$$
$$C^* = C_w^* + \varepsilon(T_w^* - T_\infty^*)e^{n^*t^*} \text{ at } y^* = 0,$$
$$u^* \to U_\infty^*, T^* \to T_\infty^*, C^* \to C_\infty^*, \text{ as } y^* \to \infty \tag{7}$$

where U_p^* is the wall dimensional velocity; C_w^* and T_w' are the wall dimensional concentration, and temperature, respectively; U_∞^*, C_∞^* and T_∞^* are the free stream dimensional velocity, concentration and temperature, respectively; and n^* is the constant.

It is clear from Eq. (1) that the suction velocity normal to the plate is either a constant or a function of time. Hence the suction velocity normal to the plate is taken as:

$$v^* = -v_0 \tag{8}$$

where v_0 is a scale of suction velocity which is a nonzero positive constant. The negative sign indicates that the suction is towards the plate. Outside the boundary layer, Eq. (2) gives:

$$\frac{1}{\rho}\frac{dp^*}{dx^*} = -\frac{\varphi\upsilon}{K^*}U_\infty^* \tag{9}$$

To render dimensionless solutions and facilitate analytical analysis, the following dimensionless variables are defined:

$$u = \frac{u^*}{U_\infty^*},\ y = \frac{y^* v_0}{\upsilon},\ U_p = \frac{U_p'}{U_\infty'},\ n = \frac{n^*\upsilon}{v_0^2},$$
$$t = \frac{t^* v_0^2}{\upsilon},\ \lambda = \frac{\sigma}{\varphi},\ \theta = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*},\ C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*}, \tag{10}$$

In view of Eqs. (5-10), Eqs. (2-4) are reduced to the following non-dimensional form:

$$\frac{\partial u}{\partial t}-\frac{\partial u}{\partial y}=\frac{\partial^2 u}{\partial y^2}+Gr\theta+GcC+\frac{1}{k}\left(1-u\right) \quad (11)$$

$$\lambda\frac{\partial \theta}{\partial t}-\frac{\partial \theta}{\partial y}=\frac{1}{\Gamma}\frac{\partial^2 \theta}{\partial y^2}+Q\theta \quad (12)$$

$$\frac{\partial C}{\partial t}-\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-KrC+So\frac{\partial^2 \theta}{\partial y^2} \quad (13)$$

The corresponding dimensionless boundary conditions are:

$$u=U_p,\ \theta=1+\varepsilon e^{nt},\ C=1+\varepsilon e^{nt} \text{ at } y=0,$$
$$u\to 1, \theta\to 0, C\to 0 \text{ as } y\to\infty.$$

where $\Gamma=\frac{3R\Pr}{3R+4}$ and $Gr=\frac{g\beta\upsilon\left(T_w^*-T_\infty^*\right)}{U_\infty^* v_0^2}$ are the thermal Grashof numbers, $Gc=\frac{g\beta^*\upsilon\left(C_w^*-C_\infty^*\right)}{U_\infty^* v_0^2}$ is the solutal Grashof number, $k=\frac{k^* {v_0}^2}{\varphi\upsilon^2}$ is the permeability of porous parameter, $\Pr=\frac{\rho C_p\varphi\upsilon}{k}$ is the Prandtl number, $R=\frac{K_e k}{4\varphi\sigma_s {T_\infty}^3}$ is the thermal radiation parameter, $Q=\frac{Q_0 v}{\varphi\rho C_p {v_0}^2}$ is the heat source parameter, $Sc=\frac{\upsilon}{D}$ is the Schmidt number, $Kr=\frac{Kr^*\upsilon}{v_0^2}$ is the chemical reaction parameter, and $So=\frac{D_1\left({T_w}^*-{T_\infty}^*\right)}{\upsilon\left({C_w}^*-{C_\infty}^*\right)}$

3. Solution of the problem

Eqs. (11-13) are coupled; these equations and nonlinear partial differential equations cannot be solved in closed form. However, these equations can be reduced to a set of ordinary differential equations, which can be solved analytically. This can be done by representing the velocity, temperature, and concentration of the fluid in the neighborhood of the plate as:

$$\begin{aligned}
u\left(y,t\right)&=u_0\left(y\right)+\varepsilon e^{nt}u_1\left(y\right)+0(\varepsilon)^2+.......,\\
\theta\left(y,t\right)&=\theta_0\left(y\right)+\varepsilon e^{nt}\theta_1\left(y\right)+0(\varepsilon)^2+.......,\\
C\left(y,t\right)&=C_0\left(y\right)+\varepsilon e^{nt}C_1\left(y\right)+0(\varepsilon)^2+.......,
\end{aligned} \quad (14)$$

Substituting Eq. (14) in Eqs. (11-13), equating the harmonic and non-harmonic the higher order terms of $0\left(\varepsilon^2\right)$, the following equations can be obtained:

$$\begin{aligned}
&u_0''+u_0'-\frac{1}{k}u_0=-\frac{1}{k}-Gr\theta_0-GcC_0\\
&u_1''+u_1'-M_1u_1=-Gr\theta_1-GcC_1\\
&\theta_0''+\Gamma\theta_0'+\Gamma Q\theta_0=0\\
&\theta_1''+\Gamma\theta_1'+\Gamma M_2\theta_1=0\\
&C_0''+ScC_0'-ScKrC_0=-ScS_0\theta_0''\\
&C_1''+ScC_1'-M_3ScC_1=-ScS_0\theta_1''
\end{aligned} \quad (15)$$

where $M_1=\frac{1}{k}+n$, $M_2=Q-n\lambda$, $M_3=Kr+n$.

The prime denotes ordinary differentiation with respect to y. The corresponding boundary conditions can be written as:

$$\begin{aligned}
&u_0=U_p, u_1=0, \theta_0=1,\\
&\theta_1=1,\ C_0=1,\ C_1=1 \text{ at y=0}\\
&\theta_1\to 0,\ C_0\to 0,\ C_1\to 0 \text{ as } y\to\infty
\end{aligned} \quad (16)$$

Solving Eq. (15) subject to boundary conditions of Eq. (16), the velocity, temperature, and concentration distributions in the boundary layer can be obtained as:

$$\begin{aligned}
u(y,t)=&\left(A_7e^{-m_5y}+1-A_5e^{-m_5y}+A_6e^{-m_1y}\right)\\
&\varepsilon e^{nt}\left(A_{10}e^{-m_6y}-A_8e^{-m_4y}+A_9e^{-m_2y}\right)
\end{aligned} \quad (17)$$

$$\theta(y,t)=\left(e^{-m_1y}\right)+\varepsilon e^{nt}\left(e^{-m_2y}\right) \quad (18)$$

$$\begin{aligned}
C(y,t)=&\left(A_2e^{-m_3y}-A_1e^{-m_1y}\right)\\
&+\varepsilon e^{nt}\left(A_4e^{-m_4y}+A_3e^{-m_2y}\right)
\end{aligned} \quad (19)$$

where the expressions for the constants are given in the appendix.
The skin-friction, Nusselt number, and Sherwood number are important physical parameters for this type of boundary layer flow. These parameters can be defined and determined as follows:
Knowing the velocity field, skin-friction at the plate can be obtained, which in non-dimensional form is given by:

$$Cf = \frac{\tau'}{\rho U_0 v_0} = \left(\frac{\partial u}{\partial y}\right)_{y=0} = \left(\frac{\partial u_0}{\partial y} + \varepsilon e^{nt}\frac{\partial u_1}{\partial y}\right)_{y=0}$$
$$= \begin{matrix}\left(-m_5 A_7 + m_3 A_5 - m_1 A_6\right) \\ + \varepsilon e^{nt}\left(-m_6 A_{10} + A_8 m_4 - A_9 m_2\right)\end{matrix} \qquad (20)$$

Knowing the temperature field, the rate of heat transfer coefficient can be obtained, which in the non-dimensional form, in term of the number, is given by:

$$\text{Nu} = -x\frac{\left(\frac{\partial T}{\partial y'}\right)_{y'=0}}{\left(T'_w - T'_\infty\right)} \Rightarrow Nu\,\text{Re}_x^{-1}$$
$$= -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -\left(\frac{\partial \theta_0}{\partial y} + \varepsilon e^{nt}\frac{\partial \theta_1}{\partial y}\right)_{y=0}$$
$$= m_1 + \varepsilon e^{nt} m_2 \qquad (21)$$

Knowing the concentration field, the rate of mass transfer coefficient can be obtained, which in the non-dimensional form, in terms of the Sherwood number, is given by:

$$\text{Sh} = -x\frac{\left(\frac{\partial C}{\partial y'}\right)_{y'=0}}{\left(C'_w - C'_\infty\right)} \Rightarrow Sh\,\text{Re}_x^{-1}$$
$$= -\left(\frac{\partial C}{\partial y}\right)_{y=0} = -\left(\frac{\partial C_0}{\partial y} + \varepsilon e^{nt}\frac{\partial C_1}{\partial y}\right)_{y=0}$$
$$= \left(m_3 A_2 - m_1 A_1\right) + \varepsilon e^{nt}\left(m_4 A_4 - m_2 A_3\right) \qquad (22)$$

where $\text{Re}_x = v_0 x / \nu$ is the local Reynolds number.

4. Results and discussion

The system of ordinary differential Eq. (15) with boundary conditions of Eq. (16) is solved analytically by employing the Perturbation technique. The solutions are obtained for the steady and unsteady velocity, temperature, and concentration fields from the Eqs. (17-19). The expressions obtained in previous section are studied with the help of graphs from Figs. 2- 10 and Tables 1-3. The effects of various physical parameters viz., the thermal Grashof number *Gr*, the solutal Grashof number *Gc*, Prandtl number *Pr*, Schmidt number *Sc*, the radiation parameter *R*, the permeability of the porous medium *k*, the heat generation parameter *Q*, the chemical reaction parameter *Kr*, and the Soret number *So*. In the present study, the default parametric values are adopted as: *Gr=2.0, Gc=2.0, k=5.0,* λ *=1.4, Sc=0.2, R=5.0, Kr=2.0, Q=0.1, Pr=0.71, So=0.5, Up=0.4, A=0.5, t=1.0, n=0.1, and* ε *=0.01.*
It is evident from Fig. 2 that greater cooling of the surface leads to an increase in *Gr*, and *Gc* results in an increase in the velocity. The *Gr* signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. The *Gc* is the ratio of the species buoyancy force to the viscous hydrodynamic force. It is due to the fact that the increase in the value of *Gr* and the *Gc* has the tendency to increase the thermal and mass buoyancy effect.

Table 1. Effect of various physical parameter on Skin friction for *k=5.0, Q=0.1,* λ *=1.4, Pr=0.71, R=5.0,Sc=0.2,Kr=2.0,So=0.5,Up=0.4* values.

Gr	*Gc*	*K*	*Cf*	*Nu*	*Sh*
2.0	2.0	5.0	6.3439	0.4369	0.7292
3.0	2.0	5.0	8.0208	0.4369	0.7292
4.0	2.0	5.0	9.6977	0.4369	0.7292
2.0	3.0	5.0	7.4878	0.4369	0.7292
2.0	4.0	5.0	8.6316	0.4369	0.7292
2.0	2.0	6.0	6.5443	0.4369	0.7292
2.0	2.0	7.0	6.7037	0.4369	0.7292

Table 2. Effect of various physical parameter on Skin friction for *Gr=2.0,Gc=2.0,k=5.0,* λ *=1.4, Sc=0.2, Kr=2.0, So=0.5, Up=0.4* values.

Pr	*R*	*Q*	*Cf*	*Nu*	*Sh*
0.71	5.0	0.1	6.3439	0.4369	0.7292
1.0	5.0	0.1	5.4114	0.6811	0.7109
1.5	5.0	0.1	4.6688	1.0875	0.6763
0.71	6.0	0.1	6.2273	0.4594	0.7277
0.71	7.0	0.1	6.1449	0.4763	0.7265
0.71	5.0	0.01	5.8027	0.5577	0.7205
0.71	5.0	0.015	5.8225	0.5525	0.7209

Table 3. Effect of various physical parameter on Skin friction for *Gr=2.0, Gc=2.0, k=5.0, Q=0.1,* λ *=1.4, Pr=0.71, R=5.0, Up=0.4* values.

Sc	*Kr*	*S0*	*Cf*	*Nu*	*Sh*
0.2	2.0	0.5	6.3439	0.4369	0.7292
0.3	2.0	0.5	5.9556	0.4369	0.9231
0.4	2.0	0.5	5.7103	0.4369	1.0962
0.2	3.0	0.5	6.0305	0.4369	0.8739
0.2	4.0	0.5	5.8254	0.4369	0.9958
0.2	2.0	0.6	6.3580	0.4369	0.7254
0.2	2.0	0.7	6.3721	0.4369	0.7215

The effect of the permeability of the porous medium *k*, and the radiation parameter *R* on the velocity field are shown in Fig. 3. The *R* defines the relative contribution of conduction heat transfer to thermal radiation transfer. It is seen from Fig.3 that the velocity increases with the increase of *k*, while it decreases with the increase of *R*.

The effect of *Pr* and *Q* on the velocity and temperature fields are shown in Figs. 4 and 5, respectively. From these figures it is observed that velocity and temperature decreases when *Pr* increases, whereas they increase when *Q* increases. The reason is that the conductivity of the fluid and therefore heat is able to diffuse away from the heated surface more rapidly for higher values of *Pr*. Hence in the case of smaller *Pr,* the thermal boundary layer is thicker and the rate of heat transfer is reduced.

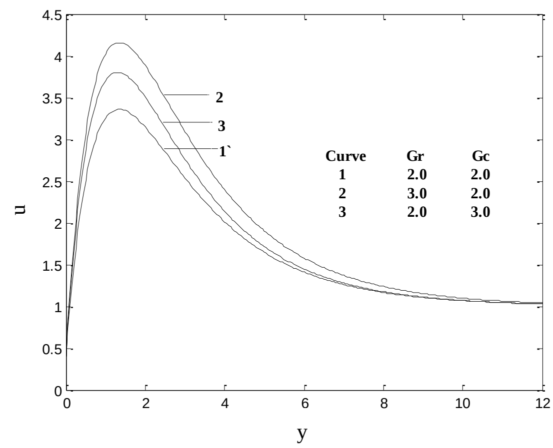

Fig. 2. The graph of *u* against *y* for varies values of *Gr* and *Gc*.

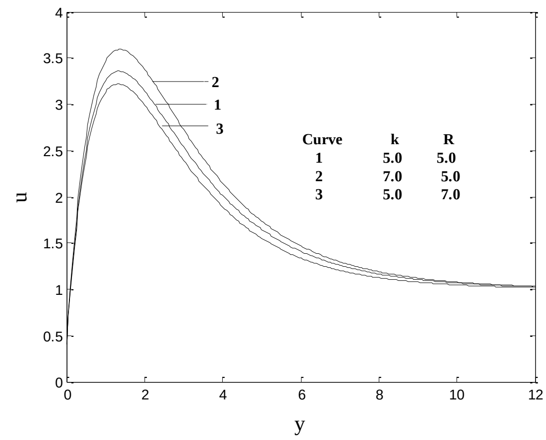

Fig. 3. The graph of *u* against *y* for varies values of *k* and *R*.

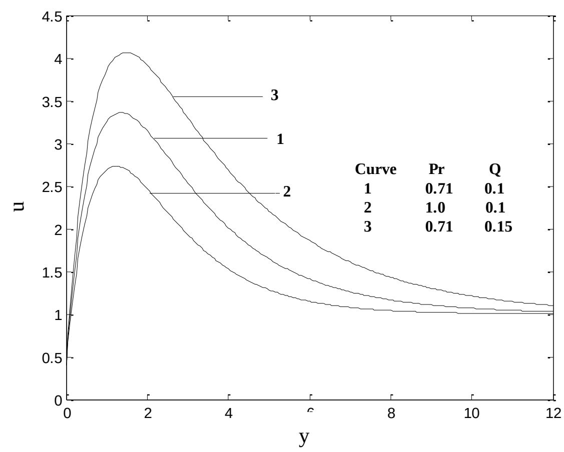

Fig. 4. The graph of *u* against *y* for varies values of *Pr* and *Q*.

Figs. 5 and 9 show the variation of velocity and concentration profiles for various values of *Sc* and *So*. The *Sc* embodies the ratio of the momentum to the mass diffusivity. It, therefore, quantifies the relative effectiveness of the momentum and mass transport by diffusion in the hydrodynamic (velocity) and concentration (species) boundary layers.

It is observed from these figuresthat increasing in the values of *Sc*, decreases velocity and concentration distribution, while the increase in the values of *So*, increases velocity and concentration distribution.

Figs. 6 and 10 show the dimensionless velocity and concentration profiles for different values of *Kr*. It can be seen that both velocity and the concentration profiles decreases with the increase of *Kr*. Fig. 7 depicts the temperature profiles for different values of *R,* and it is observed that an increase in the *R* decreases the temperature.

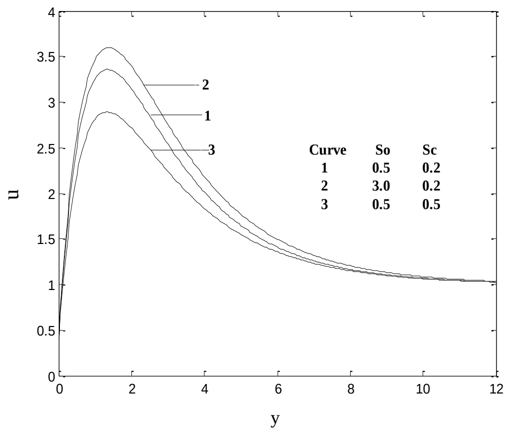

Fig. 5. The graph of *u* against *y* for varies values of *So* and *Sc*.

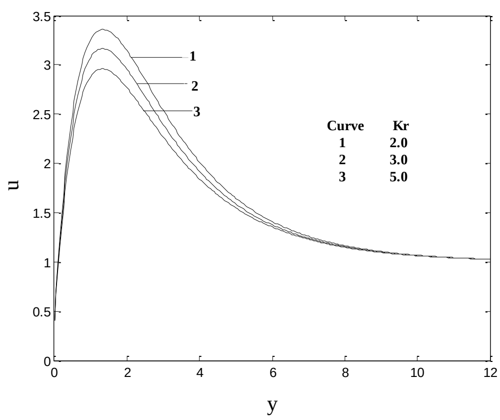

Fig. 6. The graph of *u* against *y* for varies values of *Kr*.

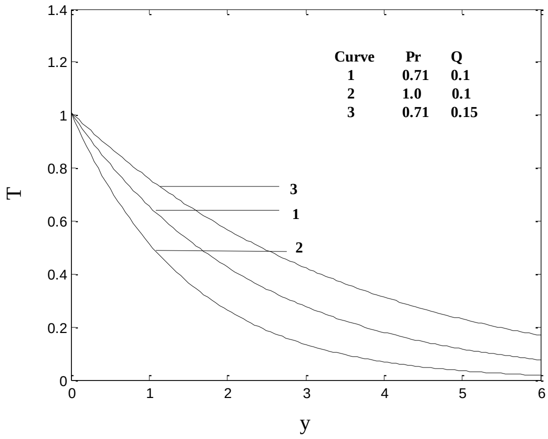

Fig. 7. The graph of *T* against *y* for varies values of *Pr* and *Q*.

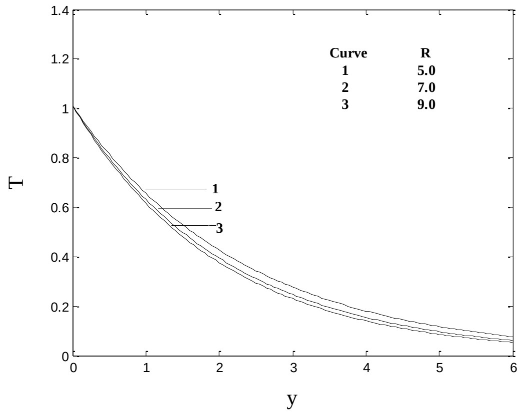

Fig. 8. The graph of *T* against *y* for varies values of *R*.

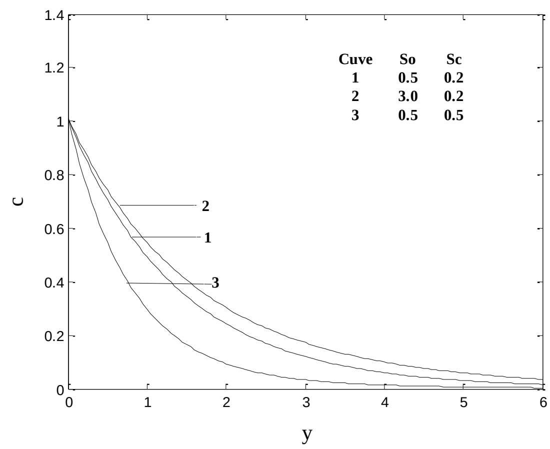

Fig. 9. The graph of *C* against *y* for varies values of *So and Sc*.

Table 4. Computations showing comparison with Ibrahim's results [21] for *Gc = 2.0, K= 5.0,* λ *=1.4, Pr = 0.71, R = 5.0, Kr = 2.0, Q = 0.1,* U_p *= 0.4, A = 0.5, t = 1.0, n = 0.1,* ε *= 0.01* and *S0 = 0.0.*

			Ibrahim's results [21]			Present results		
Gr	Pr	Sc	*Cf*	*Nu*	*Sh*	*Cf*	*Nu*	*Sh*
2.0	0.71	0.2	6.2735	0.4369	0.7487	6.2735	0.4369	0.7487
3.0			7.9503			7.9503		
	1.0		5.3134	0.6811		5.3134	0.6811	
		0.6	5.3141		1.4519	5.3141		1.4519

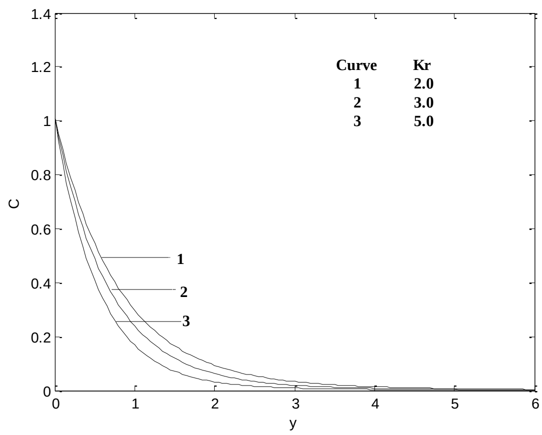

Fig. 10. The graph of *C* against *y* for varies values of *Kr.*

The variation in the local skin-friction coefficient, local couple stress, local Nusselt number, and local Sherwood number for various parameters are investigated through Tables 1 - 3. The behavior of theses physical parameters is self-evident from Tables 3 and 4 and hence they are not discussed any further to keep brevity.

For the validity of the present work, the obtained results were compared with the available results of Ibrahim [21] in the absence of the Soret number. The present result appears to be in good agreement with the Ibrahim's results (see Table 4).

5. Conclusions

In this paper, a theoretical analysis has been done to study the effects of chemical reaction and Soret effects on free convective heat and mass transfer flow through a highly porous medium in presence of chemical reaction. The results obtained are in agreement with the usual flow. It has been noticed that the velocity in the boundary layer increases with Grashof and modified Grashof number (buoyancy parameters). It is also observed the velocity and concentration increases with decreasing Schmidt number and chemical reaction parameter. It is found that the increase in values of *Gr, Gc, k, Q* and *So* increases skin-friction factor. Nusselt number increases the values of *Pr* and *R.* In addition, the value of Sherwood number increases as *Sc* and *Kr* increase.This work can further be extended by considering some more relevant fluid parameters like magnetic field parameter, Dufour number, and Eckert number.

Appendix

$$m_1 = \frac{\Gamma + \sqrt{\Gamma^2 - 4Q\Gamma}}{2},$$

$$m_2 = \frac{\Gamma + \sqrt{\Gamma^2 - 4\Gamma M_2}}{2},$$

$$m_3 = \frac{Sc + \sqrt{Sc^2 + 4ScKr}}{2},$$

$$m_4 = \frac{Sc + \sqrt{Sc^2 + 4ScM_3}}{2},$$

$$m_5 = \frac{1 + \sqrt{1 + \left(\frac{4}{k}\right)}}{2},$$

$$m_6 = \frac{1 + \sqrt{1 + 4M_1}}{2},$$

$$A_1 = \frac{m_1^2 SoSc}{m_1^2 - Scm_1 - ScKr},$$

$$A_2 = 1 + A_1,$$

$$A3 = \frac{m_2^2 SoSc}{m_2^2 - Scm_2 - ScM_3},$$

$A_4 = 1 + A_3$,

$A_5 = \dfrac{GcA_2}{m_3^{\,2} - m_3 - (1/k)}$,

$A_6 = \dfrac{GcA_1 - Gr}{m_1^{\,2} - m_1 - (1/k)}$,

$A_7 = U_p - 1 + A_5 - A_6$,

$A_8 = \dfrac{GcA_4}{m_4^{\,2} - m_4 - M_1}$,

$A_9 = \dfrac{GcA_3 - Gr}{m_2^{\,2} - m_2 - M_1}$,

$A_{10} = A_8 - A_9$,

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