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MHD flow over a vertical moving porous plate with viscous dissipation by considering double diffusive convection in the presence of chemical reaction

Research Article

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Abstract: The present paper analyzes the effects of first order homogeneous chemical reaction and thermal diffusion on hydromagnetic free convection heat and mass transfer flow of viscous dissipative fluid past a semi-infinite vertical moving porous plate embedded in a porous medium in the presence of thermal radiation. The fluid is considered gray, absorbing-emitting but non-scattering medium and Rosseland approximation is considered to describe the radiative heat flux in the energy equation, the plate is considered a moving with constant velocity in the direction of the flow field while the free stream velocity is assumed to follow exponentially increasing small perturbation law. It is considered that the influence of uniform magnetic field acts normal to the porous surface, which absorbs the fluid with suction velocity varying with respect to time. The results obtained have been presented through graphs and tables to observe the effects of various parameters encountered in the problem under the investigation. Numerical data for skin-friction, Nusselt and Sherwood numbers are tabulated and then discussed.

MSC: 80A20 • 65L12

Keywords: MHD • vertical plate • porous medium • heat and mass transfer • chemical reaction

1. Introduction

The study of radiative heat and mass transfer in convection flow found to be most important in industrial and technologies. The applications are often found in situation such as fiber and granules insulation, geothermal systems in the heating and cooling chamber, fossil fuel combustion, energy processes and Astro-physical flows. Further, the magneto convection place an important role in the control of mountain iron flow in the steady industrial liquid metal cooling in nuclear reactors and magnetic separation of molecular semi conducting materials. MHD flows assumes greater significance in several biological and engineering systems when the flow is considered over a permeable boundary. The effects of radiation on MHD flow and heat transfer at extremely high temperature is of prime importance in several manufacturing and in electrical industry. The study of heat and mass transfer with chemical reaction is of practical importance to engineers and scientists duo to its applications in several areas in many branches of science or engineering or technology branches. Chamkha [1] studied thermal radiation and buoyancy effects on hydro-magnetic flow over an accelerating permeable surface with heat source and sink. Thermal radiation and buoyancy effects on MHD free convection heat generation flow over an accelerating permeable surface with temperature dependent viscosity was presented by Seddek [2] . Muthucumaraswamy and Ganesan [3] investigated the effects of chemical reaction on the unsteady flow past an impulsively started semi infinite vertical plate which subjected to uniform heat flux and in the presence of heat transfer. Azzam [4] presented the radiation effects on the MHD mixed convection flow past a semi-infinite moving vertical plate for temperature differences. Muthucumaraswamy and Ganesan [6] presented the effects of suction on heat transfer along a moving vertical surface in the presence of

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chemical reaction. Ganesan and Loganadan [6] investigated radiation and mass transfer effects on flow of an incompressible viscous fluid past a moving cylinder. Raptis et al [7] studied the effects of radiation on two dimensional steady MHD optically thin gray gas flow along an infinite vertical plate taking into account the induced magnetic field. Kandasamy et al. [8] studied the effects of chemical reaction, heat and mass transfer along a wedge with heat source and concentration in the presence of suction or injection. The effect of a chemical reaction of an electrically conducting viscous fluid over a non-linearly semi-infinite stretching heat in the presence of a constant magnetic field which is normal to the sheet was studied by Raptis and Perdikis [9] . Unsteady MHD free convection flow of a compressible fluid past a moving vertical plate in the presence of radiative heat transfer was studied by Mbeledogu et al [10]. Seddeek et al [11] studied the effects of chemical reaction, radiation and variable viscosity on hydro-magnetic mixed convection heat and mass transfer for Hiemenz flow through porous media. The effects of chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi infinite vertical permeable moving plate with heat source and suction was studied by Ibrahim et al. [12]. Patil and Kulkarni [13] presented the effects of chemical reaction on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation. Shankar et al [14] investigated the radiation and mass transfer effects on unsteady MHD free convection fluid flow embedded in a porous medium with heat generation/absorption. MHD flow over a vertical moving porous plate with heat generation by considering double diffusive convection was studied by Ramana Reddy et al [15] . Effects of chemical reaction and radiation absorption on an unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate embedded in a porous medium with heat and suction was presented by Kesavaiah et al [16] . Gnaneswara Reddy [17] studied heat and mass transfer effects on unsteady MHD flow of a chemically reacting fluid past an impulsively started vertical plate with radiation.

In most of the studies mentioned above, viscous dissipation effect is neglected. The viscous dissipation effect is expected to be relevant for fluids with high values of dynamic viscosity as for high velocity flows. The viscous dissipation heat is important in the natural convective flows, when the field is of extreme size or at extremely low temperature or in high gravitational field. Mahmud Alam and Abdus Sattar [18] studided unsteady MHD free convection and mass transfer flow in a rotating system with Hall current, viscous dissipation and Joule heating. MHD free convection and mass transfer with Hall current, viscous dissipation, Joule heating and thermal diffusion was studied by Singh [19] . Cookey et al. [20] have studied the influence of viscous dissipation and radiation on unsteady MHD free convection flow past an infinite heated vertical plate in a porous medium with time dependent suction. Ramachandra Prasad and Bhaskar Reddy [21] presented radiation and mass transfer effects on an unsteady MHD convection flow past a semi-infinite vertical permeable moving plate embedded in a porous medium with viscous dissipation. Pandya and Shukla [22] presented Soret - Dufour and radiation effects on MHD flow over an inclined porous plate embedded in porous medium with viscous dissipation. Alam [23] studied transient thermophoretic particle deposition on MHD free convective and viscous dissipative flow along an inclined surface considering Soret - Dufour effects.

In view of all such studies, the unsteady MHD double diffusive convection for heat and mass transfer with radiation and viscous dissipation in the presence of chemical reaction gain importance and attention in the recent years. In view of this, the main object of the present investigation is to study the effect of a first order homogeneous chemical reaction, thermal radiation, viscous dissipation and thermal diffusion on the unsteady MHD double diffusive free convection fluid flow past a vertical porous plate. In the course of analysis it is assumed that the flow direction in the presence of applied transverse magnetic field. Further, it is assumed that the free stream to consist of a mean velocity and temperature over which are super imposed and or exponentially varying with respect time.

2. Mathematical analysis

Two-dimensional unsteady flow of a laminar, incompressible, electrically conducting, viscous dissipative fluid flow past a semi-infinite vertical moving porous plate embedded in a uniform porous medium and subjected to a uniform transverse magnetic field in the presence of a pressure gradient with double diffusive free convection, thermal radiation, thermal diffusion and chemical reaction has been considered. The $x'-$ axis is taken along the plate in the upward direction and $y'-$ axis normal to it. The fluid is assumed to be a gray, absorbing, emitting but non-scattering medium. The radiative heat flux in the $x'-$ direction is considered negligible in comparison with that in the $y'-$ direction. It is assumed that there is no applied voltage of which implies the absence of an electric field. The transversely applied magnetic field and magnetic Reynolds number are very small and hence the induced magnetic field is negligible. The MHD term is derived from an order of magnitude analysis of the full Navier-Stokes equation. It is assumed here that the whole size of the porous plate is significantly larger than a characteristic microscope length scale of the porous medium. We regard the porous medium as an assemblage of small identical spherical particles fixed in space. A homogeneous first-order chemical reaction between the fluid and the species concentration. The chemical reactions are taken place in the flow and all thermo physical properties are assumed to be constant of the linear momentum equation which is approximation. The fluid properties are assumed to be constant except that the influence of density variation with temperature and concentration has been considered in the body force term. Due to the semi-infinite plane surface assumption furthermore, the flow variables are the functions of y' and t' only. The governing equation for this investigation is based on the balances of mass, linear momentum, energy and species concentration. Taking into consideration the assumptions made above, these equations can be written in Cartesian frame of reference, as follows:

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

$$\rho\left(\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'}\right) = -\frac{\partial p'}{\partial x'} + \mu\frac{\partial^2 u'}{\partial y'^2} - \rho g - \sigma B_0^2 u' - \frac{\mu}{K'}u' - U_\infty \tag{2}$$

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho C_p}\frac{\partial q_r'}{\partial y'} + \frac{\nu}{C_p}\left(\frac{\partial u'}{\partial y'}\right)^2 \tag{3}$$

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

where u', v' are the velocity components in x', y' directions respectively, t' - the time, ρ- the fluid density, g' - the acceleration due to gravity, β and β' - the thermal and concentration expansion coefficients respectively, T'- the temperature of the fluid, T'_w- the temperature of the fluid near the plate, T'_∞- the temperature of the fluid far away from the plate, C'- the species concentration of the fluid, C'_w- the species concentration of the fluid near the plate, C'_∞- the species concentration of the fluid far away from the plate, ν- the kinematic viscosity, σ- the electrical conductivity of the fluid, C_p- the specific heat at the constant pressure, μ- the viscosity of the fluid, K'- the permeability of the porous medium, k- thermal conductivity of the fluid, B_0- the magnetic induction, D_M- the mass diffusivity, D_T- the thermal diffusivity, n'- frequency of oscillation.

It is assumed that the porous plate moves with a constant velocity u_p in the direction of the fluid flow, and free stream velocity U'_∞- follows exponentially increasing small perturbation law. in addition, it is assumed that the temperature and concentration at the wall as well as the suction velocity are exponentially varying with time.

The boundary conditions for the velocity, temperature and concentration fields in non- dimensional form are given as follows:

$$\left.\begin{array}{l} u' = u'_p, T' = T'_w + \varepsilon(T'_w - T'_\infty)e^{in't'}, C' = C'_w + \varepsilon(C'_w - C'_\infty)e^{in't'} \text{ at } y' = 0 \\ u' \to U'_\infty = U_0(1 + \varepsilon e^{in't'}), T' \to T'_\infty, C' \to C'_\infty \text{ as } y' \to \infty \end{array}\right\} \tag{5}$$

Now from Eq. (1) it can be seen that the suction velocity at the plate surface is a function of time only, Hence, the suction velocity normal to the plate is assumed it in the following exponential form:

$$v' = -v_0(1 + \epsilon A e^{in't'}) \tag{6}$$

where A is a real positive constant, ϵ and A are small less than unity and v_0 is a scale of suction velocity which is a non - zero positive constant. In the fee stream, from Eq. (2), we get

$$\rho\frac{dU'_\infty}{dt'} = -\frac{\partial p'}{\partial x'} - \rho_\infty g - \frac{\mu}{K'}U'_\infty - \sigma B_0^2 U'_\infty \tag{7}$$

Eliminating $\frac{\partial p'}{\partial x'}$ between Eq. (2) and Eq. (7), we obtain

$$\rho\left(\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'}\right) = (\rho_\infty - \rho)g + \rho\frac{dU_\infty}{dt'} + \mu\frac{\partial^2 u'}{\partial y'^2} + \frac{\mu}{K'}(U'_\infty - u') + \sigma B_0^2(U'_\infty - u') \tag{8}$$

By making the use of the equation of the state

$$\rho_\infty - \rho = \rho\beta(T' - T'_\infty) + \rho\beta^\star(C' - C'_\infty) \tag{9}$$

Substituting Eq. (9) into Eq. (8), we obtain

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \frac{dU'_\infty}{dt'} + \nu\frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T'_\infty) + g\beta^\star(C' - C'_\infty) + \frac{\nu}{K'}(U'_\infty - u') + \sigma B_0^2(U'_\infty - u') \tag{10}$$

The third term on the RHS of momentum Eq. (10) denote body force term due to non - uniform temperature, the fourth term denote body force term due to non - uniform concentration. the radiative heat flux term by using Rosseland approximation given by

$$q'_r = -\frac{4\sigma'}{3k_1}\frac{\partial T'^4}{\partial y'} \tag{11}$$

where σ' and k_1 are respectively the Stefan - Boltzman constant and the mean absorption coefficient. We assume that the temperature differences within the flow are sufficiently small such that T'^4 can 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, we obtain

$$T'^4 = 4T'^3_\infty T' - 3T'^4_\infty \tag{12}$$

By using Eqs. (11) and Eq. (12), Eq. (3) reduces to

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} + \frac{16\sigma^\star T'^4_\infty}{3\rho C_p k'_1}\frac{\partial^2 T'}{\partial y'^2} + \frac{\nu}{C_p}\left(\frac{\partial u'}{\partial y'}\right)^2 \tag{13}$$

In order to write the governing equations and the boundary conditions in dimensionless form, the following non-dimensional quantities are introduced.

$$\begin{aligned}
&y = \frac{v_0 y'}{\nu}, t = \frac{v_0^2 t'}{\nu}, n = \frac{\nu n'}{v_0^2}, u = \frac{u'}{U_0}, U' = U_\infty U_0, u'_p = U_p U_0, \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \phi = \frac{C' - C'_\infty}{C'_w - C'_\infty}, K = \frac{K' v_0^2}{\nu^2},\\
&M = \frac{B_0}{v_0}\sqrt{\frac{\sigma\nu}{\rho}}, S_c = \frac{\nu}{D_M}, P_r = \frac{\mu C_p}{k}, \mathrm{G}_r = \frac{g\beta\nu(T'_w - T'_\infty)}{v_0^2 U_0}, G_m = \frac{g\beta^*\nu(C'_w - C'_\infty)}{v_0^2 U_0}, k_r = \frac{k'_r\nu}{v_0^2},\\
&R = \frac{4\sigma^* T'_\infty}{k'_1 k}, S_r = \frac{D_T(T'_w - T'_\infty)}{\nu(C'_w - C'_\infty)}, E_c = \frac{v_0^2}{C_p(T'_w - T'_\infty)} \text{ and } N_1 = M + 1/K
\end{aligned} \tag{14}$$

On substitution of Eqs. (6) and (14) into Eqs. (10), (13) and (4) the following governing equations are obtained in non-dimensional form:

$$\frac{\partial u}{\partial t} - \left(1 + \epsilon A e^{int}\right)\frac{\partial u}{\partial y} = \frac{dU_\infty}{dt} + \frac{\partial^2 u}{\partial y^2} + G_r\theta + G_m\phi + N_1(U_\infty - u) \tag{15}$$

$$\frac{\partial\theta}{\partial t} - \left(1 + \epsilon A e^{int}\right)\frac{\partial\theta}{\partial y} = \frac{1}{P_r}\left(1 + \frac{4R}{3}\right)\frac{\partial^2\theta}{\partial y^2} + E_c\left(\frac{\partial u}{\partial y}\right)^2 \tag{16}$$

$$\frac{\partial\phi}{\partial t} - \left(1 + \epsilon A e^{int}\right)\frac{\partial\phi}{\partial y} = \frac{1}{S_c}\frac{\partial^2\phi}{\partial y^2} + S_r\frac{\partial^2\theta}{\partial y^2} - k_r\phi \tag{17}$$

G_r, G_m, M, K, P_r, R, E_c, S_c, S_r and k_r are the thermal Grashof number, solutal Grashof number, magnetic parameter, porosity parameter, Prandtl number, radiation parameter, Eckert number, Schmidt number, Soret number and chemical reaction parameter respectively.

The corresponding boundary conditions for velocity, temperature and concentration fields in non-dimensional form are:

$$[\begin{array}{ll} u = U_p, \theta = 1 + \varepsilon e^{int}, \phi = 1 + \varepsilon e^{int} & \text{at} \quad y = 0 \\ u \to U_\infty = (1 + \varepsilon e^{\mathrm{int}}), \theta \to 0, \phi \to 0 & \text{as} \quad y \to \infty \end{array} \tag{18}$$

3. Method of solution

By applying the Galerkin FEM for Eq. (15) over the two-nodded linear element (e), $\left(y_j \le y \le y_k\right)$ is

$$\int_{y_j}^{y_k} \psi^{(e)T}\left[\frac{\partial^2 u^{(e)}}{\partial y^2} + J_1\frac{\partial u^{(e)}}{\partial y} - \frac{\partial u^{(e)}}{\partial t} - N_1 u^{(e)} + (G_r\theta + G_m\phi + J_2)\right] dy = 0 \tag{19}$$

where $J_1 = 1 + \epsilon A e^{int}$ and $J_2 = \dfrac{dU_\infty}{dt} + NU_\infty$.

Integrating the first term in Eq. (19) by parts and neglecting the first term in the resulting equation, since the derivative $\dfrac{du}{dy}$ is not specified at either ends of the element (e), $(y_j \le y \le y_k)$, we obtain

$$\int_{y_j}^{y_k} \frac{\partial \psi^{(e)T}}{\partial y}\frac{\partial u^{(e)}}{\partial y} - \int_{y_j}^{y_k} \psi^{(e)T}\left[J_1\frac{\partial u^{(e)}}{\partial y} - \frac{\partial u^{(e)}}{\partial t} - N_1 u^{(e)} - (G_r\theta + G_m\phi - J_2)\right] dy = 0 \tag{20}$$

Finite element model may be obtained from Eq. (20) by substituting finite element approximation over the two-nodded linear element (e), $(y_j \le y \le y_k)$ of the form:

$$u^{(e)} = \psi^{(e)}\chi^{(e)} \tag{21}$$

Here $\psi^{(e)} = [\psi_j, \psi_k]$ and $\chi^{(e)} = [u_j, u_k]$

where u_j, u_k are the velocity components at j^{th} and k^{th} nodes of the typical element(e), $(y_j \le y \le y_k)$ and ψ_j, ψ_k are the basis functions defined as:

$\psi_j = \dfrac{y_k - y}{y_k - y_j}$ and $\psi_k = \dfrac{y - y_j}{y_k - y_j}$.

Substituting Eq. (21) into Eq. (20) , assembling the element equations by inter-element connectivity for two consecutive elements $y_{i-1} \le y \le y_i$ and $y_i \le y \le y_{i+1}$, put row corresponding to the node to zero, we obtain

$$u^{\bullet}_{i-1} + 4u^{\bullet}_i + u^{\bullet}_{i+1} = \frac{1}{h^2}(6 - 3J_1 h - Nh^2)u_{i-1} - \frac{4}{h^2}(3 + Nh^2)u_i + \frac{1}{h^2}(6 + 3J_1 h - Nh^2)u_{i+1} + 6(G_r\theta + G_m\phi - J_2) \tag{22}$$

Applying the trapezoidal rule to Eq. (22) and using the Crank-Nicholson method we have

$$\begin{aligned}&\left(1 - 3r + \frac{3}{2}rJ_1 h + \frac{1}{2}rN_1 h^2\right)u_{i-1}^{j+1} + (4 + 6r + 2rN_1 h^2)u_i^{j+1} + \left(1 - 3r - \frac{3}{2}rJ_1 h + \frac{1}{2}rN_1 h^2\right)u_{i+1}^{j+1} = \\ &\left(1 + 3r - \frac{3}{2}rJ_1 h - \frac{1}{2}rN_1 h^2\right)u_{i-1}^{j} + (4 - 6r - 2rN_1 h^2)u_i^{j} + \left(1 + 3r + \frac{3}{2}rJ_1 h - \frac{1}{2}rN_1 h^2\right)u_{i+1}^{j} \\ &-6k\varepsilon n sin(nt) + 6k(G_r\theta_i^j + G_m\phi_i^j) + 6kN_1(1 + \varepsilon\cos(nt))\end{aligned} \tag{23}$$

Here $N_2 = \dfrac{1}{P_r}\left(1 + \dfrac{4R}{3}\right)$, $r = \dfrac{k}{h^2}$ and h, k are the mesh sizes along y- direction and time respectively, and indices i and j refers to the space and time. Analogous equations can be obtained from Eqs. (16) and (17). In the three equations, taking $i = 1(1)n$ and using physical boundary conditions (18) , we obtain the following systems of equations:

$$A_i X_i = B_i,\ i = 1,2,3$$

where A_i's are matrices of order n and X_i, B_i are column matrices having n components. The Gauss - Seidal iteration scheme is employed to solve the above matrix system of equations. The computations are carried out until the steady state is reached. The Galerkin FEM is shown to be convergent and stable.

We present the computational results for the major physical quantities, such as the skin-friction coefficient (τ), the heat transfer coefficient (Nu) , and the mass transfer coefficient (Sh) defined by

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0},\ Nu = -\left(\frac{\partial\theta}{\partial y}\right)_{y=0}\ Sh = -\left(\frac{\partial\phi}{\partial y}\right)_{y=0}$$

4. Results and discussion

In order to get physical insight into the problem velocity profiles (u) , temperature distribution (θ) and concentration distribution (ϕ) , skin-friction coefficient (τ) , the rate of heat and mass transfer in terms of Nusselt number (Nu) and Sherwood number (Sh) have been discussed by assigning numerical values to various parameters appeared in the problem. The numerical data of these results are presented through graphs and tables.

Figs. 1-2 show the effects of Prandtl number P_r on the temperature and velocity fields respectively. From Fig. 1, it is seen that an increase in the Prandtl number decreases the temperature and temperature boundary layer. The temperature is observed to decrease steeply and exponentially away from the plate. From Fig. 2, it can be clearly seen that an increase in the Prandtl number decreases the fluid velocity. The effects of radiation parameter R on the temperature and velocity fields are presented in the Figs. 3-4 respectively. From these figures, it can be clearly seen that the temperature and velocity of the fluid increases as increasing values of the radiation parameter. However, as we move far away from the plate the influence of the radiation parameter is found perfectly zero. The influence of viscous dissipation parameter i.e., Eckert number E_c on the temperature and velocity of the fluid are presented in Figs. 5-6 respectively. From these figures, it is observed that temperature and velocity of the fluid are enhanced as the Eckert number increases. However, the change is not that significant. Further, slightly away from the plate the dispersion in the temperature is considerable and thereafter as we move far away from the plate, the effect is not found to be significant. The effects of Schmidt number S_c on the concentration and velocity of the fluid are presented in Figs. 7-8 respectively, for $S_c = 0.22, 0.60, 0.78$ and 1.00 would corresponds to hydrogen, water vapour, ammonia and propyl-benzene respectively. It is noticed that as increase in the Schmidt number decreasing the concentration and velocity fields. However, as we move far away from the plate it is seen that, as Schmidt number increases in general the velocity decreases. Further, for relatively small values of Schmidt number, it is noticed that the velocity decreases rapidly and thereafter, it increases. The influence of Soret number S_r on the concentration and velocity of the fluid are presented in Figs. 9-10 respectively. From these figures, it can be seen that for increasing values of Soret number increases the concentration and velocity of the fluid. Further, for relatively small values of Soret number, it is noticed that the velocity of the fluid increases rapidly near the plate and thereafter, it decreases. The effects of the chemical reaction parameter k_r on the concentration and velocity of the fluid are shown in the Figs. 11-12 respectively. It is observed from these figures that an increase in the chemical reaction parameter leads to decrease in concentration and velocity of the fluid. The influence of magnetic parameter M on the velocity of the fluid is presented in the Fig. 13 It can be seen that an increase in the magnetic parameter decreases the fluid velocity to some extent and thereafter it increases. However, the behavior is found to be not uniform throughout the analysis. The effects of porosity parameter

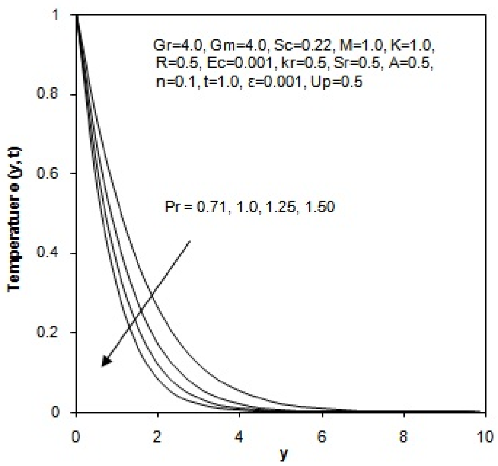

Fig. 1. Effect of Prandtl number P_r on the Temperature field

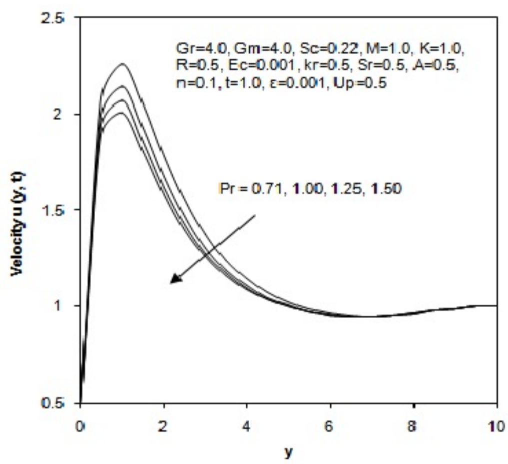

Fig. 2. Effect of Prandtl number P_r on the velocity field

Table 1. Numerical data for skin-friction coefficient (τ)

G_r	G_m	M	K	τ
2.0	2.0	1.0	1.0	2.389988
4.0	2.0	1.0	1.0	2.787614
2.0	4.0	1.0	1.0	3.187604
2.0	2.0	1.5	1.0	1.083249
2.0	2.0	1.0	1.5	3.054408

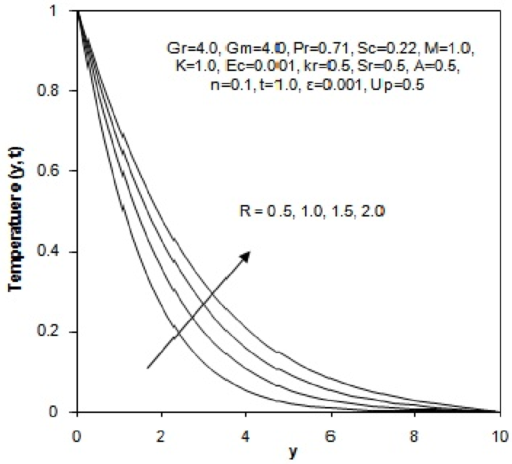

Fig. 3. Effect of Radiation parameter R on the temperature filed

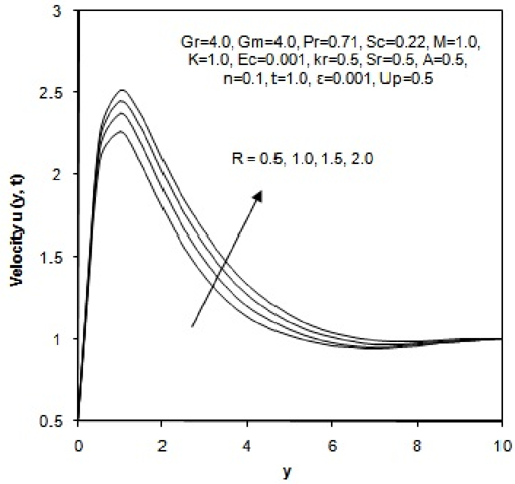

Fig. 4. Effect of Radiation parameter R on the velocity filed

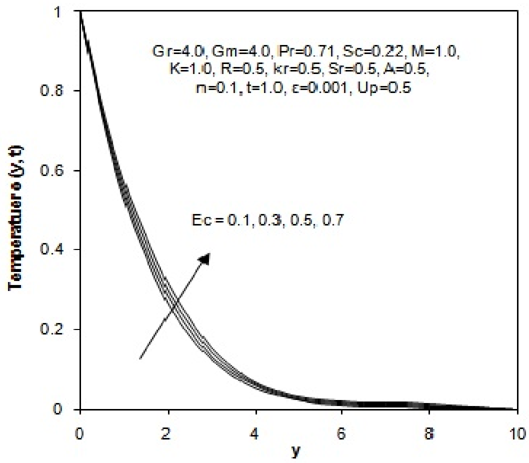

Fig. 5. Effect of Eckert number E_c on the temperature filed

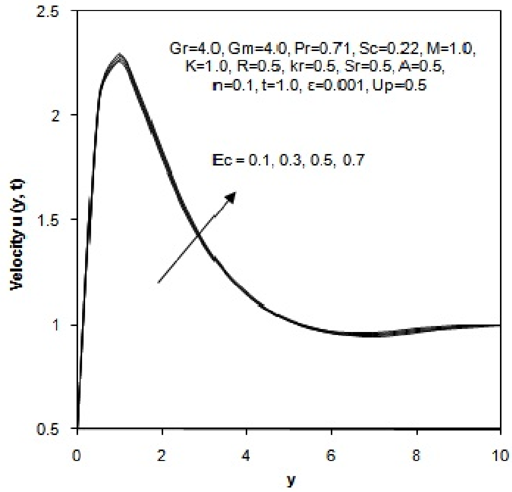

Fig. 6. Effect of Eckert number E_c on the velocity filed

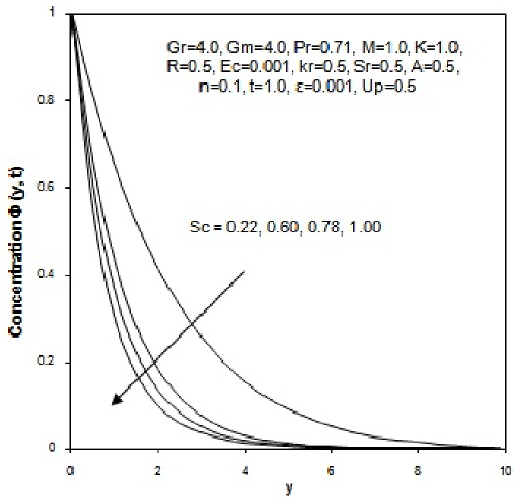

Fig. 7. Effect of Schmidt number S_c on the concentration field

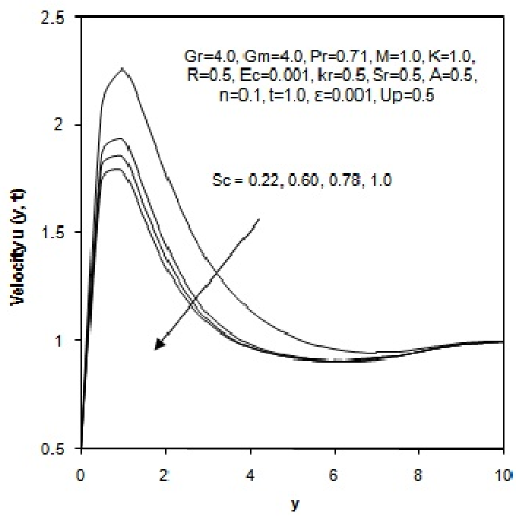

Fig. 8. Effect of Schmidt number S_c on the velocity field

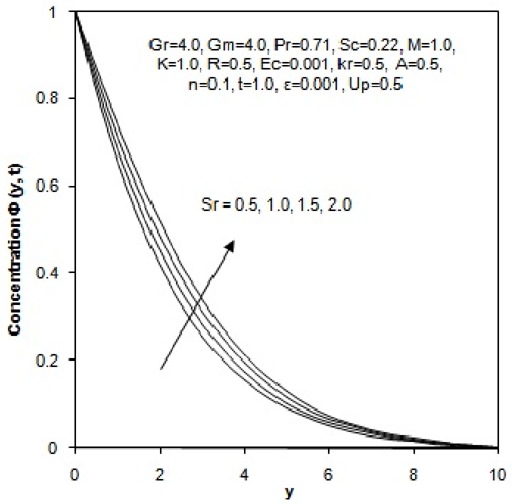

Fig. 9. Effect of Soret number S_r on the concentration field

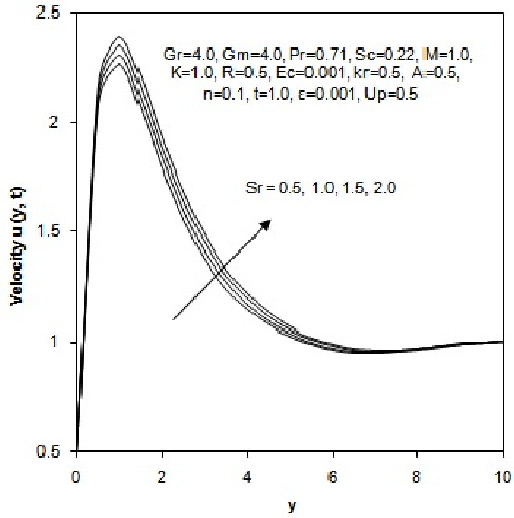

Fig. 10. Effect of Soret number S_r on the velocity field

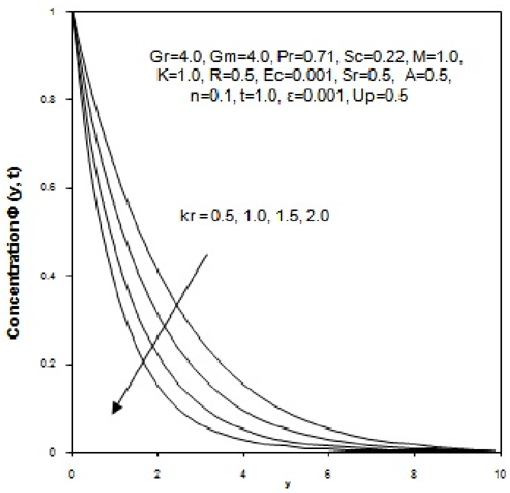

Fig. 11. Effect of chemical reaction parameter k_r on the concentration field

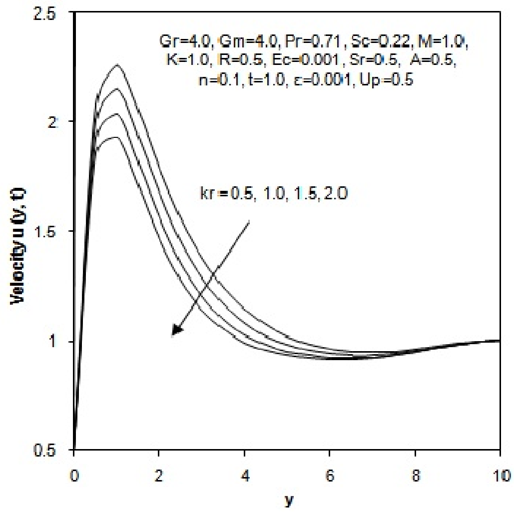

Fig. 12. Effect of chemical reaction parameter k_r on the velocity field

Table 2. Numerical data for skin-friction coefficient (τ) and Nusselt number (Nu)

P_r	R	E_c	τ	Nu
0.71	0.5	0.1	2.389988	0.755292
1.0	0.5	0.1	1.721976	1.999902
0.71	1.0	0.1	2.793142	0.592863
0.71	0.5	0.3	2.408732	0.736036

K on the velocity profiles are presented in Fig. 14. It is observed that an increase in the porosity parameter leads to increase in the fluid velocity in the boundary layer region and the influence of the porosity parameter is not same as we move away from the plate. The effects of thermal Grashof number G_r and solutal Grashof number G_m on the velocity field are presented in Figs. 15-16 respectively. It can be seen that the velocity of the fluid in the boundary layer increases as the thermal and solutal Grashof numbers increase. Such a phenomena is found to be true in the boundary layer region. However, outside the boundary layer the behavior is found to be not observable and definable. Therefore, it can be concluded that the influence of thermal Grashof number is only in the boundary layer and the effect not outside the region.

The numerical data for the skin-friction coefficient (τ) for different values of G_r, G_m, M and K are presented in

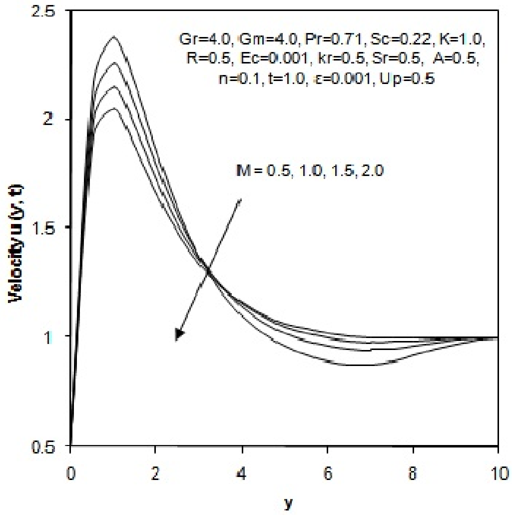

Fig. 13. Effect of magnetic parameter M on the velocity field

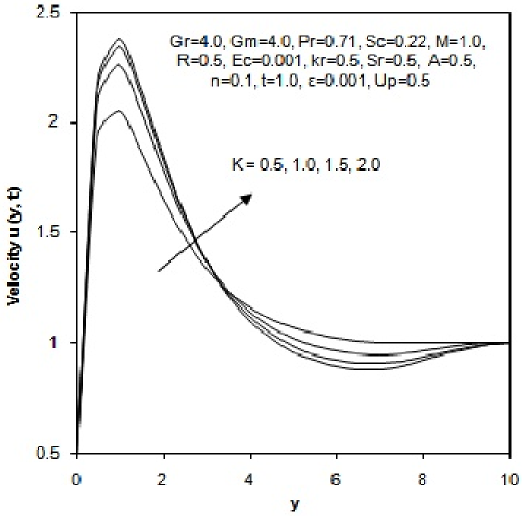

Fig. 14. Effect of porosity parameter K on the velocity field

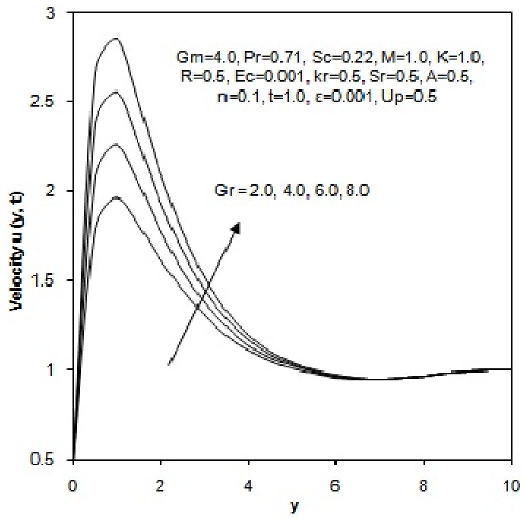

Fig. 15. Effect of thermal Grashof number G_r on the velocity field

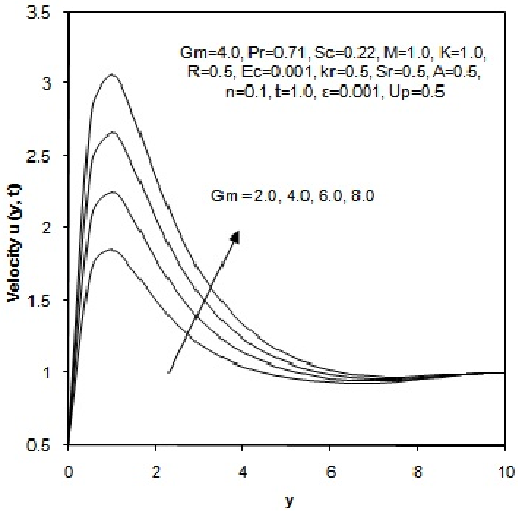

Fig. 16. Effect of solutal Grashof number G_m on the velocity field

Table 1. It is observed that an increase in G_r, G_m and K leads to increase in the skin-friction coefficient whereas an increase in M leads to decrease in the skin-friction coefficient.

The numerical data for the skin-friction coefficient (τ) and Nusselt number (Nu) for different values of P_r, R and E_c are presented in Table 2. It is observed that an increase in P_r decreases the skin-friction coefficient and increases the Nusselt number. An increase in R and E_c increases the skin-friction coefficient and decreases the Nusselt number.

The numerical data for the skin-friction coefficient (τ) and Sherwood number (Sh) for different values of S_c, S_r and k_r are presented in Table 3. It is observed that an increase in S_r and k_r decreases the skin-friction coefficient and increases in the Sherwood number. An increase in S_r increases the skin-friction coefficient and decreases in the

Table 3. Numerical data for skin-friction coefficient (τ) and Sherwood number (Sh)

$S_{(}c)$	S_r	k_r	τ	Sh
0.22	0.5	0.5	2.389988	0.199582
0.60	0.5	0.5	1.788408	0.547742
0.22	1.0	0.5	2.494910	0.125406
0.22	0.5	1.0	1.920132	0.624982

Sherwood number.

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