INTERNATIONAL JOURNAL OF CHEMICAL
REACTOR ENGINEERING

Volume 9 2011 *Article* A66

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ISSN 1542-6580

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Abstract

Magneto-hydrodynamic free convective heat and mass transfer of a viscous, incompressible, electrically conducting and chemically-reacting fluid adjacent to a vertical stretching sheet embedded in a saturated porous medium in the presence of a thermal radiation effect are investigated. The sheet is linearly stretched with uniform constant of temperature and concentration. The governing partial differential equations are transferred into a system of ordinary differential equations, which are solved numerically using a fourth order Runge-Kutta scheme with the shooting method. The effects of various parameters entering into the problem have been examined on the velocity and temperature profiles as well as the skin-friction coefficient, and Nusselt and Sherwood numbers are presented graphically and in tabular form.

KEYWORDS: heat and mass transfer, porous medium, MHD flow, chemical reaction

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*The authors are very thankful to the editor and the reviewers for their critical comments and constructive suggestions to improve the presentation of this paper.

1. Introduction

Coupled heat and mass transfer by natural convection in a fluid saturated porous medium has many important applications in geothermal and geophysical engineering such as the extraction of geothermal energy, the migration of moisture in fibrous insulation, under ground disposal of nuclear waste, and the spreading of chemical pollutants in saturated soil. A comprehensive reviews on this area have been made by many researchers some of them are Nield and Bejan (2006) and Ingham and Pop (1998,2002).

On the other hand, in many engineering applications such as nuclear reactor safety, combustion systems, solar collectors, metallurgy, and chemical engineering there are many transport processes that are governed by the joint action of the buoyancy forces from both thermal and mass diffusions in the presence of chemical reaction effect. Representative applications of interest include: solidification of binary alloy and crystal growth, dispersion of dissolved materials or particulate water in flows, drying and dehydration operations in chemical and food processing plants, and combustion of atomized liquid fuels. Also, the effects of thermal radiation with chemical reaction on free convection flow and mass transfer have a publication importance such as the combustion of fossil fuels, atmospheric re-entry with suborbital velocities, plasma wind tunnels, electric spacecraft propulsion, hypersonic flight through planetary atmosphere photo-dissociation, photo ionization, and geophysics. Diffusion and chemical reaction in an isothermal laminar flow along a soluble flat plate were studied by Fairbanks and Wike (1950). The effects of chemical reaction and mass transfer on flow past an impulsively infinite vertical plate with constant heat flux were studied by Das et al. (1994). Andersson et al. (1994) have studied the flow and mass diffusion of a chemical species with first-order and higher order reactions over a linearly stretching surface. Anjalidevi and Kandasamy (1999) have analyzed the steady laminar flow along a semi-infinite horizontal plate in the presence of a species concentration and chemical reaction. They (2002) have also studied effects of chemical reaction, heat and mass transfer on non-linear MHD laminar boundary layer flow over a wedge with suction and injection. The laminar mixed convective heat and mass transfer over a horizontal moving plate with the chemical-reaction effect were studied by Fan et al. (1998). Takhar et al. (2000) have investigated the flow and mass diffusion of chemical species with first-order and higher order reactions over a continuously stretching sheet with the magnetic field effect. Muthucumaraswamy (2002) has studied the effects of a chemical reaction on a moving isothermal vertical infinitely long surface with suction. Analytical solutions for the overall heat and mass transfer on MHD flow of a uniformly stretched vertical permeable surface with the effects of heat generation/absorption and chemical reaction were presented by Chamkha (2003).

The effects of radiation and chemical reaction on MHD free convective flow and mass transfer past a vertical isothermal cone surface were investigated by Afify (2004). Kandasamy et al. (2005) studied the nonlinear MHD flow with heat and mass transfer characteristics on a vertical stretching surface with chemical reaction and thermal stratification effects. Seddeek (2005) has studied the homogeneous chemical reaction of first-order in boundary-layer hydromagnetic flow with heat and mass transfer over a heated surface. Abo-Eldahab and Salem (2005) have analyzed the MHD flow and heat transfer with the diffusion and chemical reaction effects over a moving cylinder. Mohamed et al. (2007) have investigated the influence of chemical reaction on the coupled heat and mass transfer by natural convection from a vertical stretching surface in the presence of a space- or temperature-dependent heat source effect. EL-Kabeir and Modather (2007) studied the effects of chemical reaction, heat and mass transfer on MHD flow over a vertical isothermal cone surface in micropolar fluids with heat generation/absorption. The influence of chemical reaction on heat and mass transfer by natural convection from vertical surfaces embedded in fluid-saturated porous medium subjected to a chemical reaction was analyzed by Postelnicu (2007). The influences of thermal diffusion and magnetic field on combined free-forced convection and mass transfer flow past a vertical porous flat plate, in the presence of heat generation were studied numerically by Rahman (2008). Rashad and EL-Kabeir (2010) have studied the effects of thermal/mass diffusions and chemical reaction on the heat and mass transfer by unsteady mixed convection boundary layer past an impermeable vertical stretching sheet embedded in a porous medium.

The purpose of this work is to generalize the work of Abo-Eldahab (2001) through the inclusion of permeability of the porous medium, chemical reaction, magnetic field and thermal radiation effects on the heat and mass transfer by natural convective boundary layer flow over a vertical stretching sheet embedded in porous medium. The boundary-layer equations are transformed by a similarity transformation into a system of nonlinear ordinary differential equations, which is solved numerically for various parameters by employing a fourth-order Runge-Kutta scheme with the shooting method. Numerical results are presented in the form of velocity, temperature and concentration profiles within the boundary layer for different parameters entering into the analysis. Also the effects of the pertinent parameters on the local skin friction coefficient the local Nusselt and Sherwood numbers are also discussed.

2. Mathematical Analysis

Consider steady, laminar, heat and mass transfer by natural convection, boundary layer flow of an electrically-conducting, chemically-reacting fluid past a linearly radiate moving vertical surface embedded in a saturated porous medium when the velocity of the fluid far away from the plate is equal to zero. The $\bar{x}$-axis is located parallel to the vertical surface and the $\bar{y}$-axis normal to it. Two equal and opposite forces are introduced along the $\bar{x}$-axis (see Fig. 1), so that the sheet is stretched keeping the origin fixed.

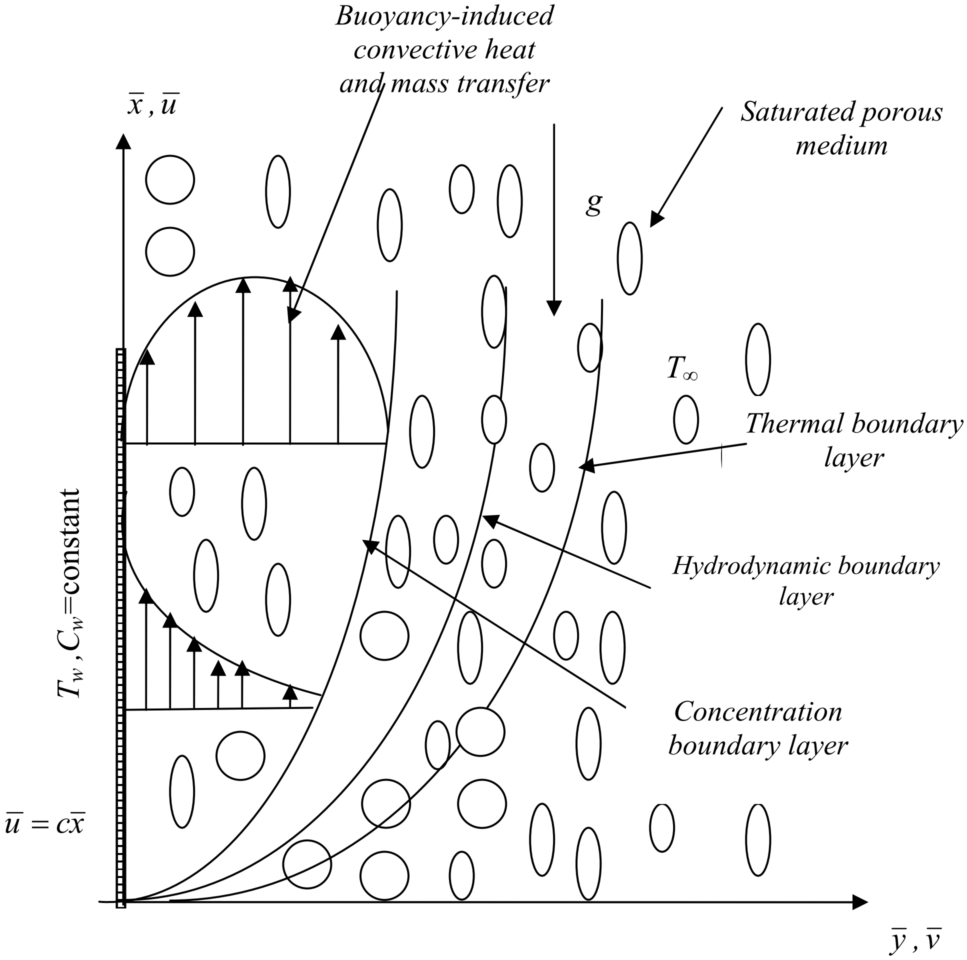


Fig. 1. Sketch of the physical model.

A magnetic field of uniform strength B_0 is imposed along the $\bar{y}$-axis which is normal to the flow direction. In addition, the radiate heat flux in the $\bar{x}$ direction is considered negligible in comparison with that in the $\bar{y}$-direction. The surface of the sheet is maintained at a constant temperature T_w and a constant concentration C_w. of a foreign fluid, which are higher than the corresponding values T_∞ and C_∞, respectively, sufficiently far away from the sheet surface. Constant fluid properties are assumed throughout the medium i.e. density, mass diffusivity, viscosity and chemical reaction rate are fixed. The Soret and Dufour effects are neglected as the concentration of diffusing species is very small in comparison to other chemical species and the concentration of species far from the wall, $C_{\infty,}$ is infinitesimally small, see Bird et al. (1992). Under the usual boundary layer and Boussinesq approximations, the governing equations for this problem can be written as (see Abo-Eldahab (2001)):

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0, \tag{1}$$

$$\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}} = \nu \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) - \frac{\nu}{K}\bar{u} - \frac{\sigma B_0^2}{\rho}\bar{u}, \tag{2}$$

$$\bar{u}\frac{\partial T}{\partial \bar{x}} + \bar{v}\frac{\partial T}{\partial \bar{y}} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial \bar{y}^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial \bar{y}}, \tag{3}$$

$$\bar{u}\frac{\partial C}{\partial \bar{x}} + \bar{v}\frac{\partial C}{\partial \bar{y}} = D\frac{\partial^2 C}{\partial \bar{y}^2} - K_1(C - C_\infty), \tag{4}$$

where $\bar{u}$ and $\bar{v}$ are the velocity components in the $\bar{x}$- and $\bar{y}$-directions, respectively, T, C and g are the fluid temperature, fluid concentration and acceleration due to gravity, respectively, ρ, ν, C_p, k, β and β^* are the fluid density, fluid kinematics viscosity, specific heat at constant pressure, thermal conductivity, coefficient of thermal expansion and coefficient of concentration expansion, respectively, σ, B_0, D, K and K_1 are the electric conductivity, magnetic induction, mass diffusivity, permeability of porous medium and dimensional chemical reaction parameter, respectively.

The appropriate boundary conditions of the problem are:

$$\bar{u} = c\bar{x},\ \bar{v} = 0,\ T = T_w,\ C = C_w \text{ at } \bar{y} = 0,$$
$$\bar{u} \to 0, T \to T_\infty, C \to C_\infty \text{ at } \bar{y} \to \infty. \tag{5}$$

where $c > 0$. It is important to remark that the radiative heat flux q^r is described according to the Rosseland approximation such that:

$$\frac{\partial q^r}{\partial \bar{y}} = -\frac{4\sigma_1}{3\chi}\frac{\partial T^4}{\partial \bar{y}}, \tag{6}$$

where σ_1 and χ are the Stefan-Boltzmann constant and the mean absorption coefficient, respectively. As done by Raptis (1998), the fluid-phase temperature differences within the flow are assumed to be sufficiently small so that T^4 may be expressed as a linear function of temperature. This is done by expanding T^4 in a Taylor series about the free-stream temperature T_∞ and neglecting higher-order terms to yield

$$T^4 = 4T_\infty^4 T - 3T_\infty^4 , \tag{7}$$

By using Eqs. (6) and (7) in the last term of Eq. (3), we obtain

$$\frac{\partial q^r}{\partial \bar{y}} = -\frac{16\sigma_1 T_\infty^3}{3\chi}\frac{\partial^2 T}{\partial \bar{y}^2} . \tag{8}$$

According to the similarity transformations used in Abo-Eldahab (2001), it is convenient to use the following non-dimensional parameters

$$x = \frac{c\bar{x}}{u_0} ,\ y = \frac{c\bar{y}}{u_0}\mathrm{Re} ,\ u = \frac{\bar{u}}{u_0} ,\ v = \frac{\bar{v}}{u_0}\mathrm{Re} ,\ \theta = \frac{T - T_\infty}{T_w - T_\infty} ,\ \phi = \frac{C - C_\infty}{C_w - C_\infty} . \tag{9}$$

Substituting equation (9) into equations (1)-(5) and dropping the bars, we obtain,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 , \tag{10}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gc\phi - \left(M + \frac{1}{Da} \right)u , \tag{11}$$

$$u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} = \frac{1}{\mathrm{Pr}}\left(1 + \frac{4}{3}R_d \right)\frac{\partial^2 \theta}{\partial y^2} , \tag{12}$$

$$u\frac{\partial \phi}{\partial x} + v\frac{\partial \phi}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} - \gamma\phi , \tag{13}$$

with the boundary conditions

$$\begin{gathered} u = x ,\ v = 0 ,\ \theta = 1 ,\ \phi = 1 \ \text{at}\ y = 0 , \\ u \to 0 , \theta \to 0 , \phi \to 0 \ \text{at}\ y \to \infty . \end{gathered} \tag{14}$$

where $M = \sigma B_0^2 / \rho c$ is the magnetic parameter, $Da = Kc / \nu$ is the Darcy number, $\mathrm{Re} = u_0 / \sqrt{c\nu}$ is the Reynolds number, $Gr = g\beta(T_w - T_\infty) / cu_0$ is the Grashof number, $Gc = g\beta^*(C_w - C_\infty) / cu_0$ is the modified Grashof number, u_0 is the characteristic of velocity, $R_d = 4\sigma_1 T_\infty^3 / k\chi$ is the radiation parameter, $\gamma = K_1 / c$ is the non-dimensional chemical reaction parameter, $\mathrm{Pr} = \mu C_p / k$ is the Prandtl number, $Sc = \nu / D$ is the Schmidt number.

Introducing the stream function ψ defined in the usual way

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x}, \tag{15}$$

where

$$\psi(y) = f(y) + xg(y). \tag{16}$$

In view of equations of (10)-(14) and by equating coefficients of x^0 and x^1, the coupled nonlinear ordinary differential equations can be obtained as:

$$f''' = f'g' - gf'' + \left(M + \frac{1}{Da}\right)f' - Gr\theta - Gc\phi, \tag{17}$$

$$g''' = g'^2 - gg'' + \left(M + \frac{1}{Da}\right)g', \tag{18}$$

$$\frac{1}{\mathrm{Pr}}\left(1 + \frac{4}{3}R_d\right)\theta'' + g\theta' = 0, \tag{19}$$

$$\frac{1}{Sc}\phi'' + g\phi' - \gamma\phi = 0. \tag{20}$$

The primes above indicate differentiation with respect to y only and the boundary conditions (14), in view of (16), are now reduced to

$$\begin{aligned} &f(0) = f'(0) = f'(\infty) = g(0) = g'(\infty) = \theta(\infty) = \phi(\infty) = 0, \\ &g'(0) = \theta(0) = \phi(0) = 1. \end{aligned} \tag{21}$$

The physical quantities of interest in this problem are the skin friction coefficient, Local Nusselt number and local Sherwood number, which are defined, respectively, by

$$\tau_w = \mu \left.\frac{\partial u}{\partial y}\right|_{y=0}, \quad Nu = -\frac{k}{\rho C_p (T_w - T_\infty)} \left.\frac{\partial T}{\partial y}\right|_{y=0}, \quad Sh = -\frac{D}{(C_w - C_\infty)} \left.\frac{\partial C}{\partial y}\right|_{y=0}. \tag{22}$$

Using (16), quantities (22) can be expressed as

$$\tau_w = \mu c \operatorname{Re}\left(f''(0) + x g''(0)\right), \quad Nu = -\frac{ck \operatorname{Re}}{u_\infty \rho C_p}\theta'(0), \quad Sh = -\frac{cD \operatorname{Re}}{u_\infty}\phi'(0). \tag{23}$$

3. Results and discussion

The system of ordinary differential equations (17)-(20) with the boundary conditions (21) have been solved numerically by applying the shooting iteration technique together with Runge-Kutta forth-order integration scheme. From the process of numerical computation, the local skin-friction coefficient, the local Nusselt and the local Sherwood numbers, which are respectively proportional to $f''(0), -g''(0), -\theta'(0)$ and $-\phi'(0)$, are also worked out and their numerical values are presented in a tabular form.

The exact solution of the Eq. (18) with boundary conditions (21) is also given by:

$$g(y) = \frac{1}{\alpha}\left(1 - e^{-\alpha y}\right), \text{ where } \alpha = (Da^{-1} + M + 1)^{1/2}, \tag{24}$$

Numerical calculations have been carried out for different values of M, Da, R_d, γ and for fixed values of Pr, Sc, Gr, and Gc.

The value of Prandtl number (Pr) is taken to be 0.71 which corresponds to air and the value of Schmidt number (Sc) is chosen to represent hydrogen at 25^0C and 1 atm. The dimensionless parameter Gr takes the value 1, which corresponds to the free convection problem positive, and the corresponding parameter Gc takes the value for low concentration.

Figures 2(a)-2(c) display typical profiles for the velocity along the sheet, temperature and concentration for various values of Darcy number *Da* and radiation parameter R_d, respectively. The presence of a porous medium in the flow presents resistance to flow, thus, this resistive force tends to slow the motion of the fluid along the sheet and causes increases in its temperature and concentration. This is depicted in Figures by the increases in the velocity profiles and decreases in the values of both the temperature and concentration as Darcy number *Da* increases. Also, it can be seen from these Figs., the velocity profiles increases, while the temperature and concentration decrease as the radiation parameter R_d increases. These behaviors cause that the hydrodynamic, thermal, and concentration boundary layers become thicker as R_d increases. This result was expected because the presence of thermal radiation works as a heat source and so the quantity of heat added to the fluid increases. Moreover, it is obvious that the governing equations (18)-(20) are uncoupled. Therefore, changes in the values of R_d will cause no changes in both of the distributions of velocity g' and concentration of fluid, and for this reason, no figures for these variables are presented herein.

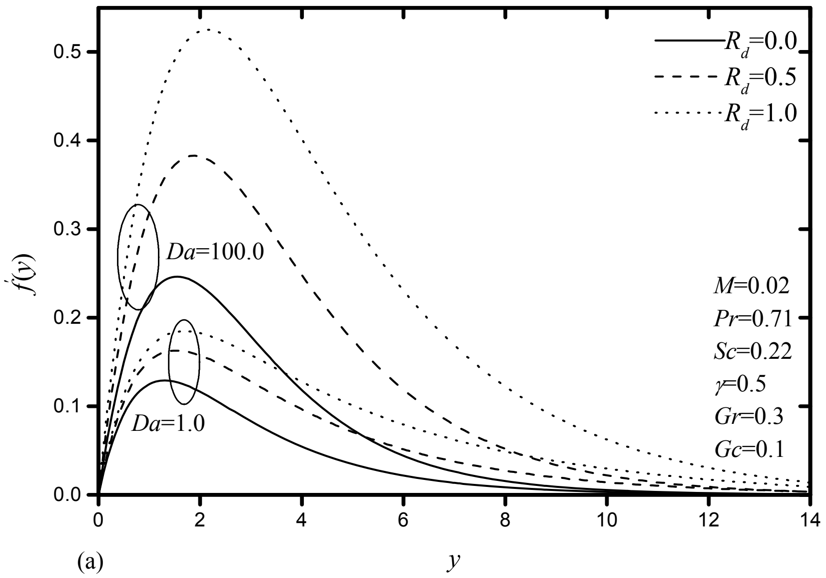


Fig. 2: Effects of Darcy number and radiation parameter on (a) velocity profiles (b) temperature profiles (c) concentration profiles.

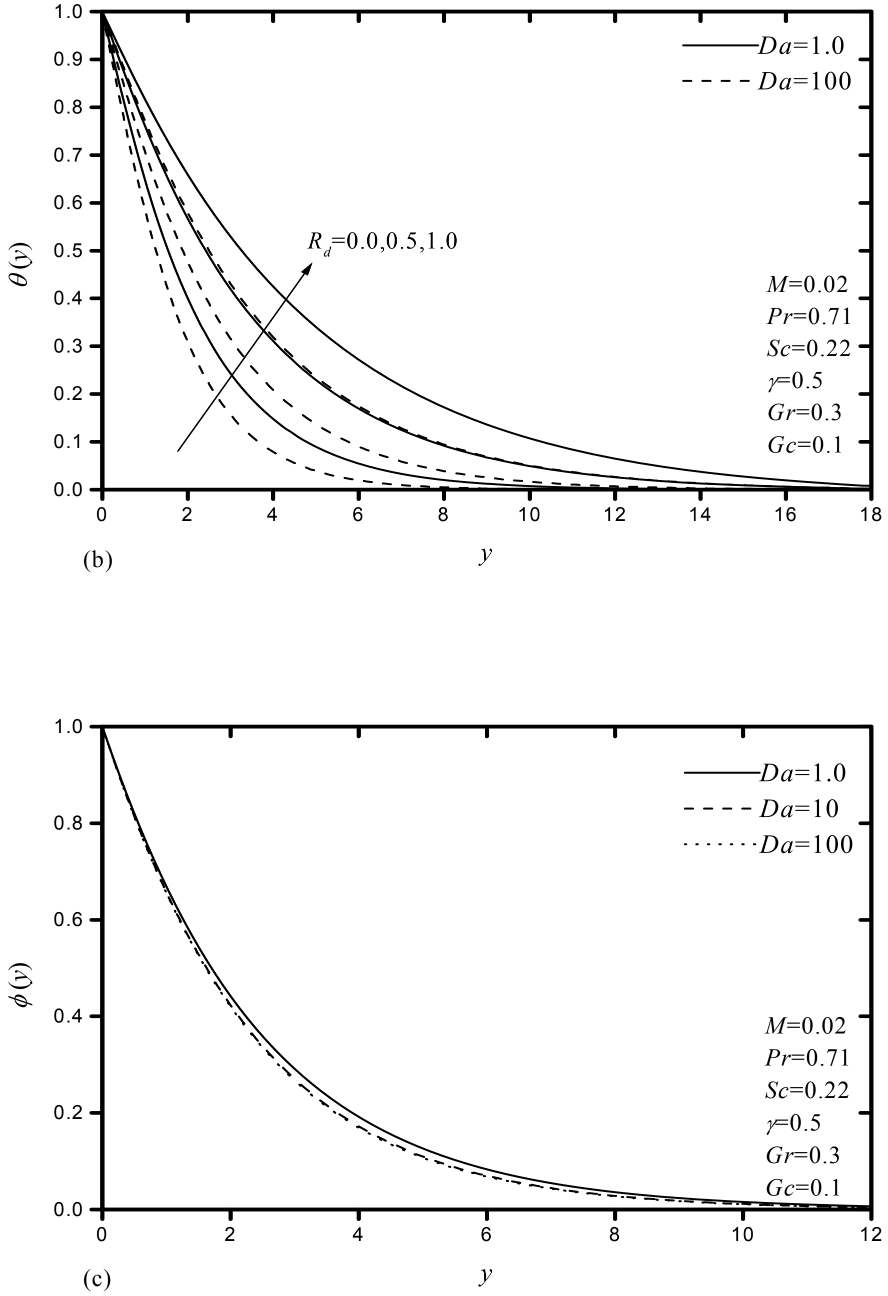


Fig. 2, continued

Figures 3(a) through 3(c) display the effects of magnetic field and chemical reaction parameter on the velocity, temperature, and concentration profiles, respectively. Application of a transverse magnetic field normal to the flow direction gives rise to the magnetic Lorentz force that acts in the opposite direction of flow causing its velocity to decrease and its temperature and concentration to increase. In addition, the hydrodynamic boundary layer decreases, whereas the thermal concentration boundary layers tend to increase as the magnetic field M increases. This result quantitatively with the expectations in Abo-Eldahab (2001). On other hand, it can be observed that, as the chemical reaction parameter γ increases, the concentration profiles increases, while, the velocity profiles decreases. Sucking decelerated fluid particles through the sheet reduce the growth of the fluid boundary layer as well as concentration boundary layers. no effect on both of the distributions of velocity g' and temperature of fluid for the same reason as obvious above.

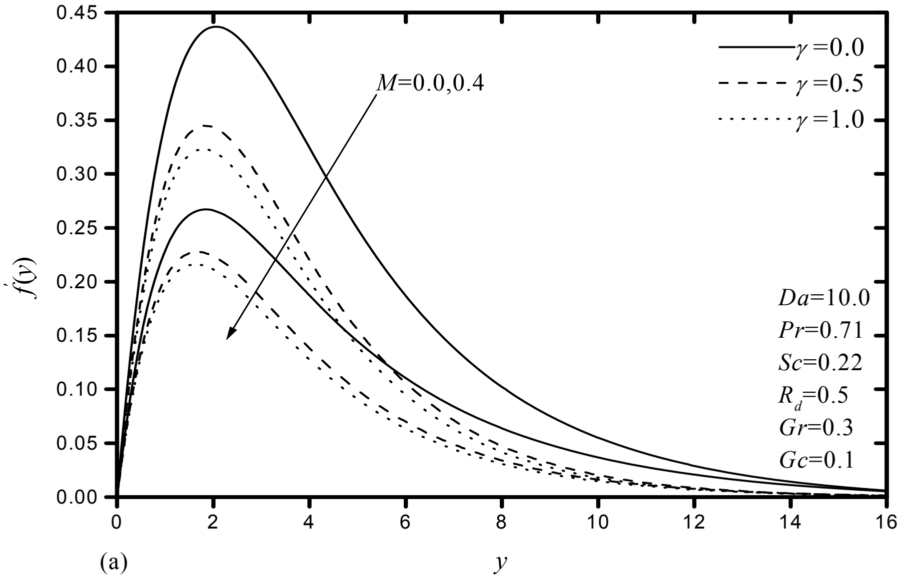
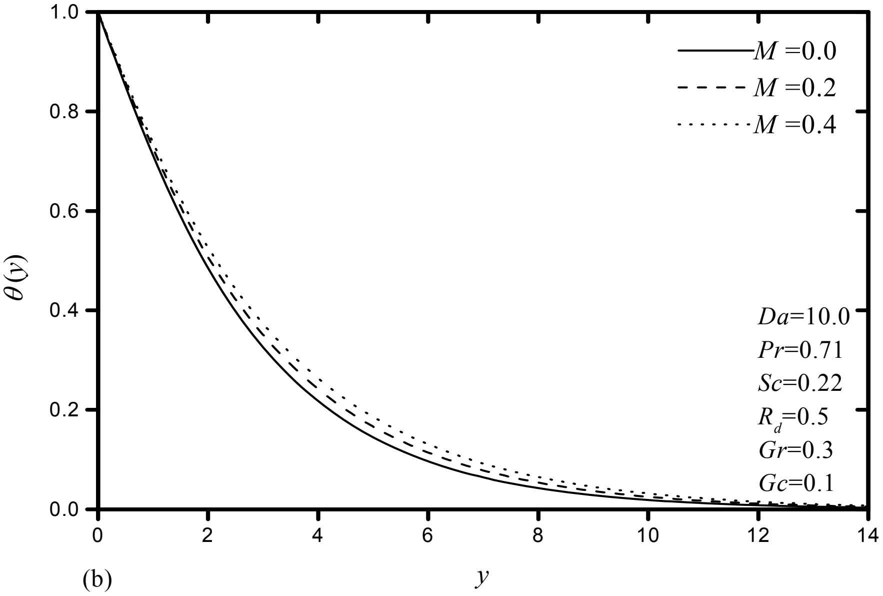


Fig. 3: Effects of magnetic and chemical reaction parameters on (a) velocity profiles (b) temperature profiles (c) concentration profiles.



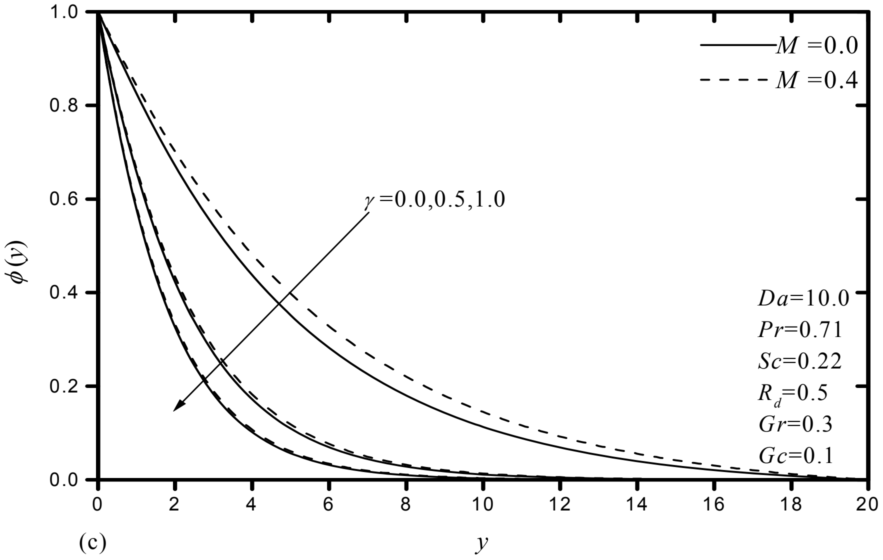


Fig. 3, continued

Finally, table 1 reports the values for the local skin-friction coefficients ($f''(0)$ and $-g''(0)$), the local Nusselt number $-\theta'(0)$ and the local Sherwood number $-\phi'(0)$ at the surface of the sheet for various values of Darcy number Da, R_d, M and γ. It is worth mentioning that the wall shear stress $f''(0)$ decreases as the chemical reaction, magnetic and radiation parameters increase whereas it increases as Darcy number increases. In addition, we observe that quantitatively the magnitude of the wall-temperature gradient decreases as the radiation parameter R_d and magnetic parameter M increase whereas it increases as Darcy number Da increases. Furthermore, the negative values of the wall-temperature gradient, for all values of the dimensionless parameters, are indicative of the physical fact that the heat flows from the sheet surface to ambient fluid the radiation effect on the rate of the heat transfer $-\theta'(0)$ is greater than that of the local skin friction $f''(0)$. Finally, it is obvious that the local Sherwood number $-\phi'(0)$ at the surface increases as the chemical reaction parameter and Darcy number increase whereas the opposite effect as magnetic parameter increases.

Table 1. Variation of $f''(0)$, $-g''(0)$, $-\theta'(0)$, $-\phi'(0)$ the plate surface with various values of M, γ, Da and R_d at Pr=0.71, Sc=0.22, Gr=0.3 and Gc=0.1.

M	γ	Da	R_d	$f''(0)$	$-g''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.0	0.0	10	0.5	0.52413	1.04881	0.30547	0.18014
0.0	0.5	10	0.5	0.46395	1.04881	0.30547	0.40124
0.0	1.0	10	0.5	0.44711	1.04881	0.30547	0.52731
0.2	0.0	10	0.5	0.43886	1.14018	0.29088	0.17050
0.2	0.5	10	0.5	0.40116	1.14018	0.29088	0.39756
0.2	1.0	10	0.5	0.38901	1.14018	0.29088	0.52466
0.4	0.0	10	0.5	0.38778	1.22475	0.27827	0.16253
0.4	0.5	10	0.5	0.36012	1.22475	0.27827	0.39447
0.4	1.0	10	0.5	0.35052	1.22475	0.27827	0.52241
0.02	0.5	1.0	0.0	0.26741	1.42127	0.38330	0.38826
0.02	0.5	1.0	0.5	0.29583	1.42127	0.25212	0.38826
0.02	0.5	1.0	1.0	0.31151	1.42127	0.19040	0.38826
0.02	0.5	10.0	0.0	0.37124	1.05830	0.44721	0.40084
0.02	0.5	10.0	0.5	0.45611	1.05830	0.30391	0.40084
0.02	0.5	10.0	1.0	0.52372	1.05830	0.23238	0.40084
0.02	0.5	100	0.0	0.39256	1.01489	0.45563	0.40271
0.02	0.5	100	0.5	0.49557	1.01489	0.31114	0.40271
0.02	0.5	100	1.0	0.58659	1.01489	0.23854	0.40271

4. Conclusions

In the present paper, we have studied theoretically the problem of the magneto-hydrodynamics free convective heat and mass transfer of a chemically-reacting fluid adjacent to a vertical stretching surface embedded in a porous medium. The effects of the transverse magnetic field, thermal radiation and chemical reaction are considered. The nonlinear boundary-layer equations were transformed and the resulting ordinary differential equations were solved numerically using numerically using a fourth order Runge-Kutta scheme with the shooting method. A representative set of numerical results for the velocity, temperature, and concentration profiles as well as the local skin-friction coefficient, the local Nusselt and the local Sherwood numbers with various values physical parameters were presented graphically and in tabular form. To the best of the authors knowledge, experimental data on the specific problem considered in this paper are lacking at present. It is hoped that the results reported in this work serves as a stimulus for experimental work.

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