International Journal of Research in Advent Technology, Vol.6, No.8, August 2018
E-ISSN: 2321-9637
Available online at www.ijrat.org

Radiation and Chemical Reaction Effects on MHD Free Convection Flow, Heat And Mass Transfer Past A Permeable Plate In Porous Medium

Hemanta Konwar
Kohima Science College, Kohima -797002, Nagaland, India
hemanta.konwar@gmail.com

Abstract- The purpose of this work is to study the effects of thermal radiation and chemical reaction on MHD flow, heat and mass transfer in free convective boundary layer flow over a moving vertical porous plate embedded in porous medium. The boundary layer equations are transformed into a system of nonlinear ordinary differential equations by suitable transformations and are solved numerically by employing Matlab's built in solver bvp4c. Numerical results are presented graphically for the radiation and the chemical reaction parameters respectively. It is found that the effects of the radiation parameter are to increase vertical velocity component of the fluid to a critical point and temperature but to decrease concentration in the boundary layer. Effects of the chemical reaction parameter are to decrease vertical velocity component and concentration but to increase temperature of the fluid in the boundary layer. It has also been observed that radiation parameter increases the skin friction coefficient and the Sherwood number but decreases the Nusselt number. The chemical reaction parameter decreases the skin friction coefficient and the Nusselt number but increases the Sherwood number.

Keywords-Vertical plate, Radiation, Chemical reaction, Porous medium, bvp4c.

1. INTRODUCTION

Studies of Magnetohydrodynamic free convection flows with heat and mass transfer along a vertical plate is receiving attention of many researchers due to its important applications in cosmic fluid dynamics, meteorology, high energy physics. MHD free convection flow past a heated vertical flat plate has been studied by many researchers like Eckert and Drake [1]; Vajravelu [2]; Raptis and Kafoussias [3]; Yih [4]; Postelnicu [5]. MHD free convection flow with simultaneous heat and mass transfer under the influence of thermal radiation and chemical reaction in porous media has attracted researchers and scientists as these processes exist in many branches of science and technology. Possible applications are in extraction of geothermal energy, chemical reactors with porous structures, nuclear reactors, chemical industries, MHD power generators, etc. Moreover, it has been observed that interaction between thermal radiation and chemical reaction have significant role to play in heat and mass transfer processes in free convection involving chemically reacting and absorbing-emitting fluids. Study of radiation and chemical reaction effects on various flows is quite complicated. Das *et al*. [6] analyzed effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction. Anjalidevi and Kandasamy [7] studied effects of chemical reaction on laminar flow along a semi infinite horizontal plate. Ingham and Pop [8, 9] and Nield and Bejan [10] made a comprehensive review on this area. Muthucumaraswamy [11] investigated effects of chemical reaction on a moving isothermal vertical infinitely long surface with suction. Seddeek [12] studied homogeneous chemical reaction of first order in boundary layer hydro-magnetic flow with heat and mass transfer over a heated plate. Ibrahim *et al.* [13] analyzed effects of the chemical reaction and radiation absorption on unsteady MHD free convection flow past a semi-infinite vertical permeable plate with heat source. Pal and Talukdar [14] by using perturbation techniques analyzed unsteady magnetohydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate. Jonnadula *et al.* [15] studied numerically the influence of thermal radiation and chemical reaction on MHD flow, heat and mass transfer over a stretching surface. Raptis [16] studied effects of thermal radiation on MHD flow past a vertical porous plate.

2. MATHEMATICAL FORMULATION

Consider two dimensional laminar, steady MHD free convection boundary layer flow of a radiating, chemically reacting, thermally and electrically conducting Newtonian incompressible viscous fluid past a moving vertical permeable plate embedded in a porous medium. Let the *x*-axis is directed upward along the plate and *y*-axis is normal to the plate. A uniform magnetic field of strength B_0 is applied normal to the flow direction. As the plate is electrically non-conducting the *y*-component of the magnetic field is zero. The magnetic Reynolds number is assumed to be small, so that the induced magnetic field can be neglected. No external electric field and electric field due to charge polarization are assumed to exist and hence the Hall Effect of Magnetohydro-dynamics is neglected. It is assumed that initially at $t = 0$ the plate is at rest and at time $t > 0$ the plate moves linearly with uniform velocity U_0 in the same direction as that of the free stream velocity. Let T and C are the free stream temperature and species concentration of the fluid. Let the temperature and species concentration at the surface of the plate are maintained at uniform temperature $T_w(> T_\infty)$ and uniform species concentration $C_w(> C_\infty)$, where T_∞ and C_∞ are temperature and species concentration of the fluid away from the plate. The buoyancy force arises from both the thermal and mass diffusion processes. It is assumed that there exists thermal radiation in *y*-direction, a homogeneous chemical reaction of first order between the diffusing species in the fluid and fluid suction is imposed at the surface of the plate. The physical model and the co-ordinate system are shown in the Fig1.

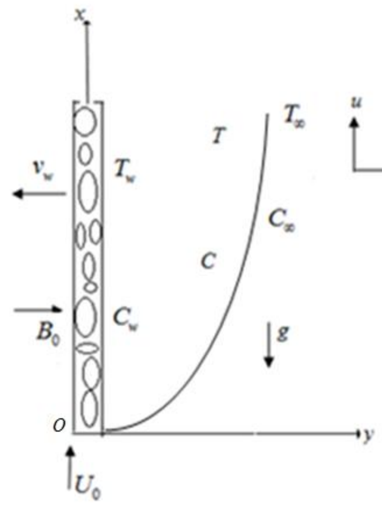

Fig1. The physical configuration of the problem

By using the Boussinesq's approximation and the Darcy-Forchheimer model, the boundary layer equations governing the flow, heat and mass transfer are as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\vartheta\frac{\partial^2 u}{\partial y^2}+g\beta_T(T-T_\infty)+g\beta_C(C-C_\infty)-\frac{\sigma_e B_0^2 u}{\rho}-\frac{\vartheta u}{K}-\frac{\beta u^2}{K}, \quad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{Dk_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}+\frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{Q_0}{\rho c_p}(T-T_\infty) \quad (3)$$

and

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+\frac{Dk_T}{T_m}\frac{\partial^2 T}{\partial y^2}-k_c(C-C_\infty) \quad (4)$$

with appropriate boundary conditions :

$$u=U_0,\ v=v_w,\ T=T_w,\ C=C_w \text{ at } y=0 \quad (5)$$

and

$$u\to 0, T\to T_\infty, C\to C_\infty \qquad \text{at } y\to\infty \quad (6)$$

where U_0 *is* the free stream velocity, $v_w(<0)$ is the suction velocity of the plate, u and v be the velocity components of the fluid along the vertical and horizontal directions, g is the acceleration due to gravity, β_T, β_C are volumetric thermal and concentration expansion coefficients, σ_e is the electrical conductivity, q_r is the radiative heat flux, Q_0 is the heat generation coefficient, ρ is the density of the fluid, μ is the dynamic viscosity, ϑ is the kinematic viscosity, K is the intrinsic permeability, β is the Forchheimer coefficient, D is the mass diffusivity, α is the thermal diffusivity, c_s is the concentration susceptibility, c_p is the specific heat at constant pressure, k_T is the thermal diffusivity ratio T_m is the mean fluid temperature and k_c is the reaction rate.

By Rosseland approximation for optically thick gray liquid, the radiative heat flux is given by the relation [17, 18]

$$q_r=\frac{-4\sigma}{3k_e}\frac{\partial T^4}{\partial y} \quad (7)$$

where σ is the Stefan-Boltzmann constant and k_e is the mean absorption coefficient respectively. If temperature differences within the flow are sufficiently small then Eq. (7) can be expanded by Taylor's series about T_∞ which after neglecting higher order terms takes the form $T^4=4T_\infty^3 T-3T_\infty^4$ (8)

3. METHOD OF SOLUTION

By using Eq. (7) and Eq. (8) and substituting the similarity transformations:

$$u=U_0 f',\ v=-\frac{1}{2}\sqrt{\frac{\vartheta U_0}{x}}f(\eta)+\frac{U_0 y}{2x}f'(\eta), \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}, \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty} \text{ and } \eta=y\sqrt{\frac{U_0}{\vartheta x}} \quad (9)$$

into the Eq. (1) to Eq. (6) it has been observed that the Eq. (1) of continuity is satisfied identically by these form of transformations. Moreover, Eq. (2) to Eq. (6) are transformed to the following non-linear coupled ordinary differential equations:

$$f'''+\frac{1}{2}ff'+Gr_x\theta+Gm_x\phi-\left(M_x+\frac{1}{Da_x Re_x}\right)f'-\frac{Fs_x}{Da_x}(f')^2=0, \quad (10)$$

$$(1+R_d Pr)\theta''+D_f Pr\phi''+\frac{1}{2}Prf\theta'+PrEc(f'')^2+\delta_x Pr\theta=0 \quad (11)$$

and

$$\phi''+ScS_T\theta''+\frac{1}{2}Scf\phi'-\gamma_x Sc\phi=0 \quad (12)$$

together with the following new boundary conditions:

$$f=f_w, f'=1, \theta=1, \phi=1 \qquad \text{at } \eta=0 \quad (13)$$

and

$$f'\to 0, \theta\to 0, \phi\to 0 \qquad \text{at } \eta\to\infty \quad (14)$$

where

$$Gr_x=\frac{g\beta_T(T_w-T_\infty)x}{U_0^2}, Gm_x=\frac{g\beta_c(C_w-C_\infty)x}{U_0^2}, M_x=\frac{\sigma_e B_0^2 x}{\rho U_0}, Da_x=\frac{K}{x^2}, Fs_x=\frac{\beta}{x}, Re_x=\frac{U_0 x}{\vartheta}, Pr=\frac{\vartheta}{\alpha}, S_T=\frac{Dk_T(T_w-T_\infty)}{\vartheta T_m(C_w-C_\infty)}, D_f=\frac{Dk_T(C_w-C_\infty)}{c_s c_p\vartheta(T_w-T_\infty)}, R_d=\frac{16\sigma T_\infty^3}{3k_e\mu c_p}, \delta_x=\frac{Q_0 x}{\rho c_p U_0}, Ec=\frac{U_0^2}{c_p(T_w-T_\infty)}, Sc=\frac{\vartheta}{D}, \gamma_x=\frac{k_c x}{U_0}, f_w=-v_w\sqrt{\frac{4x}{U_0\vartheta}}$$

are the local Grashof number, local modified Grashof number, local Hartman number, local Darcy number, local Forchheimer number, local Reynolds number, Prandtl number, Soret number, Dufour number, radiation parameter, local heat generation parameter, Eckert number, Schmidt number, local chemical reaction parameter and suction parameter respectively. Here prime denotes differentiation with respect to η.

It is to be noted that the local parameters are functions of x and generate local similarity solutions. In order to have a true similarity solution we assume the following relations [19]:

$\beta_T=\frac{a}{x}, \beta_C=\frac{b}{x}, \sigma_e=\frac{c}{x}, K=dx^2, \beta=ex, Q_0=\frac{h}{x},\ k_c=\frac{m}{x}$ where a, b, c, d, e, h and m are constants with appropriate dimensions. In view of the above relations the local parameters are now free from x and henceforth, we suppress the suffix x for simplicity.

4. RESULTS AND DISCUSSIONS

During the course of discussions the value of Pr is chosen as 0.71 that corresponds to air. The value of Sc is taken as 0.22 that corresponds to hydrogen gas. Values of other parameters are chosen arbitrarily. For Fig. 2 to Fig. 4 values are taken as Gr =10; Gm = 4; Re = 200; M = 0.5; Pr = 0.71; D_f = 0.3; Sc = 0.22; Sr =0.5; Da = 0.5; Fs =1; γ = 0.5; Ec = 0.09; δ = 0.5; f_w=1 and for Fig. 5 to Fig. 7 parameter values are taken as: Gr =10; Gm = 4; Re = 200; M = 0.5; D_f = 0.3; Sr = 0.5; Da = 0.5; Fs =1; R_d = 0.5; Ec = 0.09; δ = 0.5; f_w=1.

Vertical velocity, temperature and concentration profiles for variation of the thermal radiation parameter (R_d) and the chemical reaction parameter (γ) are shown in Fig. 2 to Fig. 4 and Fig. 5 to Fig.7.

It has been observed from the Fig. 2 that magnitude of the vertical velocity component of the fluid increases in the vicinity of the moving plate and after attaining maximum value it decreases as η increases. Moreover, with increasing values of the radiation parameter vertical velocity component of the fluid increases in the region $0 < \eta < 3.3$ and decreases in the region $\eta > 3.3$. Fig. 3 exhibits that temperature of the fluid and its associated boundary layer thickness increase with the increase in the values of the radiation parameter. It is because of the fact that radiative heat energy is absorbed by the working fluid and in turn enhances temperature of the fluid. Fig. 4 exhibits that concentration of species of the fluid and its associated boundary layer thickness decrease with the increase in the values of the radiation parameter.

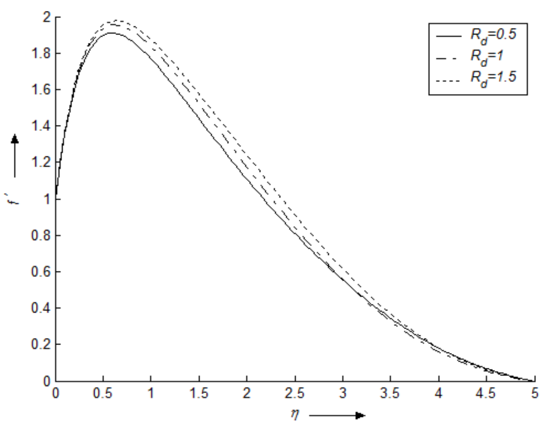

Fig 2. Vertical velocity profiles for different values of R_d

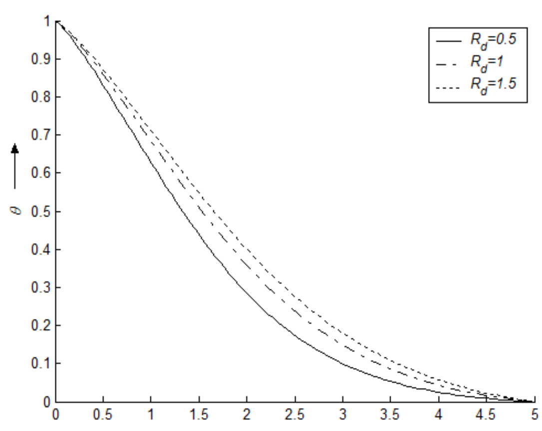

Fig 3. Temperature profiles for different values of R_d

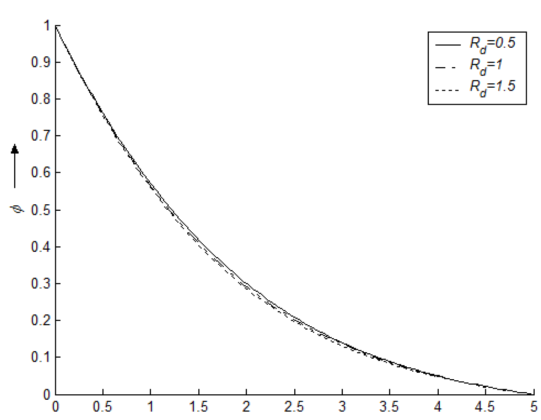

Fig 4. Concentration profiles for different values of R_d

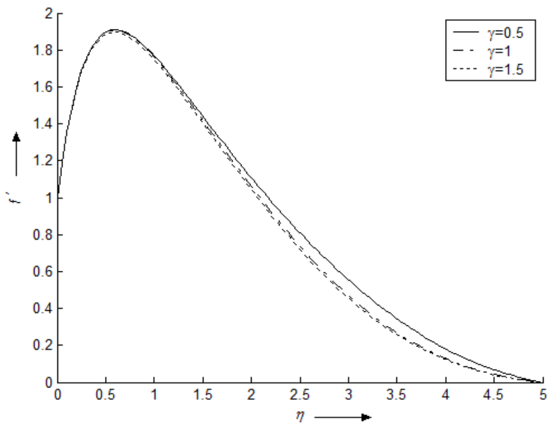

Fig 5. Vertical velocity profiles for different values of γ

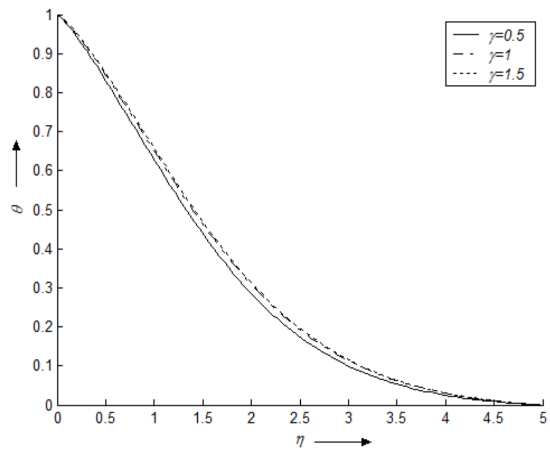

Fig 6. Temperature profiles for different values of γ

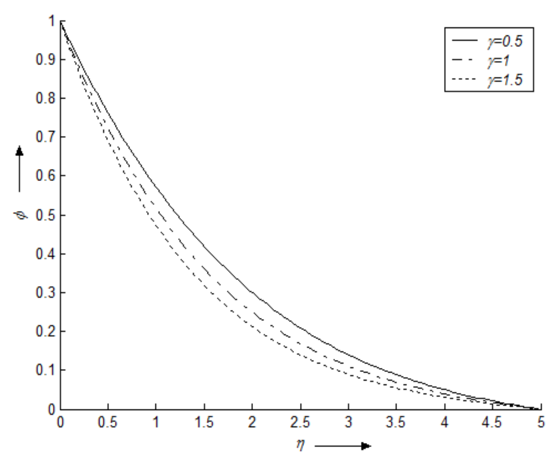

Fig 7. Concentration profiles for different values of γ

Fig. 5 reveals that magnitude of vertical velocity component of the fluid increases in the vicinity of the moving plate and after attaining maximum value it decreases exponentially as η increases. It is because of the fact that as the wall of the plate is hot relative to the surrounding so particles come in contact to the moving plate suddenly gets more kinetic energy and bounces near the wall. But, effect of increasing strength of the chemical reaction parameter is to decrease the vertical velocity component of the fluid. Fig. 6 shows that temperature of the fluid increases in the boundary layer region with the increasing strength of the chemical reaction parameter. Thus an exothermic reaction takes place within the fluid that produces heat energy and as a result temperature of the fluid rises in the boundary layer. It has been observed from the Fig. 7 that concentration of species and its associated boundary layer thickness decrease with the increasing strength of the chemical reaction parameter. As the temperature of the fluid increases due to exothermic reaction the rate of interfacial mass flux increases and reduces the local concentration by increasing the concentration gradient. As a result concentration of species decreases within the boundary layer.

The parameters of engineering importance in the present discussions are the local skin friction coefficient (C_f), the local Nusselt number (Nu) and the local Sherwood number (Sh) which are expressed as:

$$\frac{1}{2}\sqrt{Re_x}C_f = f''(0), \frac{Nu}{\sqrt{Re_x}} = -\theta'(0) \text{ and } \frac{Sh}{\sqrt{Re_x}} = -\phi'(0) \quad (15)$$

and their values are tabulated below for the radiation parameter (R_d) and the chemical reaction parameter (γ). For Table 1 the parameter values are taken as Gr=10; Gm=4; Pr=0.71; Re=200; M=0.5; D_f=0.3; Sr=0.5; Da=0.5; Fs=1; Ec=0.09; δ =0.5; Sc=0.22; f_w=1.

Table1. Numerical values of local skin friction coefficient, local Nusselt number and local Sherwood number

R_d	γ	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.5	0.5	4.1495	0.1994	0.5319
0.5	1	4.1427	0.1655	0.6369
0.5	1.5	4.1198	0.1531	0.7263
1	0.5	4.2324	0.1641	0.5376
1.5	0.5	4.2718	0.1567	0.5401

It has been observed from the Table1 that the local skin friction coefficient (C_f) and the local Sherwood number (Sh) increase but the local Nusselt number (Nu) decreases as R_d increases. The local skin friction coefficient (C_f) and the local Nusselt number (Nu) decrease but the local Sherwood number (Sh) increases as γ increases.

5. CONCLUSIONS

A study of two dimensional steady, chemically reacting, thermally and electrically conducting Newtonian incompressible viscous fluids past a moving vertical permeable plate embedded in a porous medium is carried out. The boundary layer equations are transformed into a system of nonlinear ordinary differential equations by suitable transformations and are solved numerically by employing MATLAB's built in solver bvp4c .

From the investigations it can be concluded that:

- The effect of larger values of the radiation parameter (R_d) is to increase vertical velocity component of the fluid to a certain critical point in the boundary layer and then to decrease but larger values of the radiation parameter always increases temperature and decreases concentration of the fluid everywhere in the boundary layer.
- Increasing strength of the chemical reaction parameter (γ) is to decrease vertical velocity component and concentration of species but to increase temperature of the fluid everywhere in the boundary layer.
- The local skin friction coefficient (C_f) and the local Nusselt number (Nu) decrease but the local Sherwood number (Sh) increases as γ increases.
- The local skin friction coefficient (C_f) and the local Sherwood number (Sh) increase but the local Nusselt number (Nu) decreases as R_d increases.

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