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Chemical reaction and radiation effects on MHD free convection flow through a porous medium bounded by a vertical surface with constant heat and mass flux

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Abstract

In the present paper, an analysis was carried out to investigate effects of radiation on a free convection flow bounded by a vertical surface embedded in a porous medium with constant suction velocity. It was under the influence of uniform magnetic field in the presence of a homogenous chemical reaction and viscous dissipation with constant heat and mass flux. The non-dimensional governing equations were solved analytically and the expressions were found for velocity, temperature and concentration fields. Also, the expression for skin friction near the plate was derived and the results were discussed in a table.

1. Introduction

Frequently, transformations proceed in a moving fluid, a situation encountered in a number of technological fields. A common area of interest in the field of aerodynamics analysis of thermal boundary layer problems for two-dimensional steady and incompressible laminar flows passing a wedge. Simultaneous heat and mass transfer from different geometrics embedded in porous media has many engineering and geophysical applications such as geothermal reservoirs, drying porous solids, thermal insulation, enhanced oil recovery, packed-bed catalytic reactors, cooling nuclear reactors and underground energy transport. At present, a very significant area of research in radiative heat transfer is numerical simulation of combined radiation and convection/ conduction transport processes. A massive trend of efforts has been started due to the need for optimizing industrial systems such as furnaces, ovens and boilers and the interest in the environment and in non-conventional energy sources such as using salt-gradient solar ponds for energy collection and storage. In

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particular, natural convection induced by the simultaneous action of buoyancy forces resulting from thermal and mass diffusion is of considerable interest in nature and in many industrial applications such as geophysics, oceanography, drying processes, solidification of binary alloy and chemical engineering. Frequently, transformations proceed in a moving fluid, a situation encountered in a number of technological fields.

Heat flow and mass transfer over a vertical bounded surface with constant suction velocity have been studied by many researchers. Effects of transversely magnetic field on the flow of an electrically conducting fluid past an impulsively started infinite isothermal vertical plate were studied by Soundalgekar et al. [1]. Again, Soundalgekar and Takhar [2] studied effect of radiation on the natural convection flow of a gas past a semi-infinite plate using the Cogly-Vincentine-Gilles equilibrium model. For the same gas, Takhar et al. [3] investigated effect of radiation on the MHD free convection flow past a semi-infinite vertical plate. Later, Hossain et al. [4] studied effect of radiation on free convection from a porous vertical plate. Muthucumarswamy and Kumar [5] examined thermal radiation effects on moving infinite vertical plate in the presence of variable temperature and mass diffusion. An analytical solution for unsteady free convection in porous media was studied by Magyari et al. [6]. Chamkha et al. [7] investigated effects of hydro magnetic combined heat and mass transfer by natural convection from a permeable surface embedded in a fluid saturated porous medium. Mazumdar and Deka [8] studied MHD flow past an impulsively started infinite vertical plate in the presence of thermal radiation.

The growing need for chemical reactions in chemical and hydrometallurgical industries requires studying heat and mass transfer with chemical reaction. The presence of a foreign mass in water or air causes some kind of chemical reaction. This may be present either by itself or as a mixture with air or water. In many chemical engineering processes, a chemical reaction occurs between a foreign mass and the fluid in which the plate is moving. These processes take place in numerous industrial applications like polymer production, manufacturing ceramics or glassware and food processing.

A chemical reaction can be codified as either a homogenous or heterogeneous process, depending on occurring on an interface or a single phase volume reaction. A reaction is said to be of first order if its rate is directly proportional to the concentration itself [9]. Effect of chemical reaction on heat and mass transfer in a laminar boundary layer flow has been studied under different conditions by several authors [10- 19]. Effect of a chemical reaction on a moving isothermal vertical surface with suction was studied by Muthucumarswamy [20].

Recently, Manivannan et al. [21] investigated radiation and chemical reaction effects on isothermal vertical oscillating plate with variable mass diffusion. Influence of chemical reaction and radiation on unsteady MHD free convection flow and mass transfer through viscous incompressible fluid past a heated vertical plate immersed in porous medium in the presence of heat source was investigated by Sharma et al. [22]. Vasu et al. [23] studied radiation and mass transfer effects on transient free convection flow of a dissipative fluid past semi-infinite vertical plate with uniform heat and mass constant flux. Saravana et al. [24] examined mass transfer effects on MHD viscous flow past an impulsively started infinite vertical plate with constant mass flux. O. D. Makinde [25] studied MHD boundary-layer flow and mass transfer past a vertical plate in a porous medium with constant heat flux. Recently, Mahapatra et al. [26] investigated effects of chemical reaction on a free convection flow through a porous medium bounded by a vertical infinite surface. Radiation and mass transfer effects on a free convection flow through a porous medium bounded by a vertical surface were examined by Raju et al. [27]. This problem was extended by chemical reaction and magnetic field.

The objective of the present paper was to analyze radiation effects on MHD free convection flow through porous medium bounded by a vertical surface with constant heat and mass flux in the presence of homogeneous chemical reaction. The dimensional less equations of continuity, linear momentum, energy and diffusion, which governed the flow field, were solved using a perturbation technique. The behavior of velocity, temperature, concentration and skin friction coefficient was discussed for variations in the governing parameters.

2. Mathematical analysis

An electrically conducting, radiating, viscous incompressible fluid was considered through a porous medium occupying a semi-infinite region of the space bounded by a vertical infinite surface which was discussed in the case of constant heat and mass flux. x^* - axis was taken along the plate in the vertical upward direction and the y^* - axis was normal to it. A uniform magnetic field of strength B_0 was assumed to be applied in a direction perpendicular to the surface against to the gravitational field. The transverse applied magnetic field and magnetic Reynolds number were assumed to be very small so that the induced magnetic field and the Hall effect were negligible. Concentration of the diffusing species in the binary mixture was assumed to be very small in comparison with other present chemical species; hence, Soret and Dufour were negligible. Now, under the usual Boussinesq's approximation, the governing boundary layer equations of the problem were:

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

$$v^*\frac{\partial u^*}{\partial y^*} = \vartheta\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta_T(T^* - T^*_\infty) + g\beta_C(C^* - C^*_\infty) - \frac{\sigma B_0^2}{\rho}u^* - \frac{\vartheta}{k^*}u^* \tag{2}$$

$$v^*\frac{\partial T^*}{\partial y^*} = \frac{\kappa}{\rho C_P}\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{\vartheta}{C_P}\left(\frac{\partial u^*}{\partial y^*}\right)^2 - \frac{1}{\rho C_P}\frac{\partial q_r}{\partial y^*} \tag{3}$$

$$v^*\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - k_C(C^* - C^*_\infty) \tag{4}$$

It was assumed that level of species concentration was very low; hence, the heat generated due to chemical reaction was neglected. The relevant boundary conditions were given as follows.

where u^*, v^* are velocity components in x^*, y^* directions. ρ is fluid density, ν is kinematic viscosity, c_p is specific heat at constant pressure, g is acceleration due to gravity, β and β^* are thermal and concentration expansion coefficients, respectively. B_0 is magnetic induction , α is fluid thermal diffusivity, is permeability of the porous medium, T is dimensional temperature, C is dimensional concentration, k is thermal conductivity, μ is coefficient of viscosity, D is mass diffusivity, K_c is chemical reaction parameter and F is radiation parameter. The boundary conditions for the velocity, temperature and concentration fields were:

$$u^* = 0,\ \frac{\partial T^*}{\partial y^*} = -\frac{q}{k},\ \frac{\partial C^*}{\partial y^*} = -\frac{q_w}{D} \text{ at y} = 0$$

$$u^* \to 0, T^* \to T_\infty, C^* \to C_\infty \text{ as y} \to \infty \tag{5}$$

From the continuity Eq. (1), it can be seen that suction velocity normal to the plate was either a constant or function of time. Hence, it was assumed in the form of

$$v^* = constant = -v_0 \tag{6}$$

where u^* is plate velocity, T_w and C_w are the wall dimensional temperature and concentration, respectively, T_∞ and C_∞ are free stream dimensional temperature and concentration, respectively, and v_0 is constant. In the optically thick limit, the fluid does not absorb its own emitted radiation; that is, there is no self absorption; but, it absorbs radiation emitted by the bounadries. Cookey et al. [26] showed it in the optically thick limit for a non-gray gas near equilibrium, as given below.

$$\frac{\partial q_r}{\partial y^*} = 4(T^* - T_w^*)\int_0^\infty K\lambda_w w\left(\frac{de_{b\lambda}}{dT^*}\right) / d\lambda = 4I_1(T^* - T_w^*) \tag{7}$$

In order to write the governing equations and the boundary condition in a dimensionless form, the following non-dimensional quantities can be introduced.

$$y = \frac{v_0 y^*}{v}, u = \frac{u^*}{v_0}, \theta = \frac{T^* - T_\infty^*}{\left(\frac{\vartheta q}{v_0 k}\right)}, C = \frac{C^* - C_\infty^*}{\left(\frac{\vartheta q_w^*}{v_0 D}\right)},$$

$$\mathrm{P_r} = \frac{\mu c_p}{k},\ G_r = \frac{\vartheta^2 g \beta_T q}{k v_0^4}, G_m = \frac{\vartheta^2 g \beta_C q_w^*}{k v_0^4},$$

$$S_c = \frac{\vartheta}{D}, F = \frac{4 I_1 \vartheta}{k v_0^2}\quad M = \frac{\sigma B_0^2 \vartheta}{\rho v_0^2},\ k = \frac{v_0^2 k^*}{\vartheta^2},$$

$$K_C = \frac{\vartheta K_C^*}{v_0^2}, E = \frac{v_0^3}{c_P \left(\frac{q}{k}\right) \vartheta}. \tag{8}$$

By substituting Eqs. (6) and (7) in set of Eqs. (2-4), the following non-dimensional governing equations were obtained.

$$u'' + u' = -G_r\theta - G_m C + M_1 u \tag{9}$$

where $M_1 = M + \frac{1}{k}$ $\theta'' + P_r\theta' = -P_r E u'^2 + F\theta$

(10)

$$C'' + S_c C' = K_c S_c C \tag{11}$$

where $G_r, G_m, M, K, \mathrm{Pr}, F, E, S_c$ and K_c are thermal Grashof number, Solutal Grashof number, magnetic parameter, permeability parameter, Prandtl number, thermal radiation, Eckert number, heat absorption parameter, Schmidt number and chemical reaction parameter, respectively.

The corresponding boundary conditions were

$$u = 0,\ \frac{\partial\theta}{\partial y} = -1, \frac{\partial C}{\partial y} = -1 \quad \text{at } y = 0$$

$$u \to 0,\ \theta \to 0, C \to 0 \quad \text{as } y \to \infty \tag{12}$$

3. Solution of the problem

In order to solve the coupled nonlinear system of partial differential Eqs. (9- 11) with the boundary conditions (12), the following simple perturbation was used. The governing Eqs. (9- 11) were expanded in powers of Eckert number $E (<< 1)$.

$$\left.\begin{aligned} u &= u_0 + E u_1 + O(E^2), \\ \theta &= \theta_0 + E\theta_1 + O(E^2), \\ C &= C_0 + E C_1 + O(E^2) \end{aligned}\right\} \tag{13}$$

By substituting Eq. (16) into Eqs. (11- 13), equating coefficients of the terms with the same powers of E and neglecting terms of higher order, the following equations were obtained.

3. 1. Zero-th order terms

$$u_0'' + u_0' = -G_r\theta_0 - G_m C_0 + M_1 u_0 \tag{14}$$

$$\theta_0'' + P_r\theta_0' - F\theta_0 = 0 \tag{15}$$

$$C_0'' + S_C C_0' = S_C K_C C_0 \tag{16}$$

3. 2. First order terms

$$u_1'' + u_1' = -G_r\theta_1 - G_m C_1 + M_1 u_1 \tag{17}$$

$$\theta_1'' + P_r\theta_1' - F\theta_1 = -\mathrm{P_r}\, u_0'^2 \tag{18}$$

$$C_1'' + S_C C_1' = S_C k_C C_1 \tag{19}$$

The corresponding boundary conditions were

$$u_0 = 0, u_1 = 0, \frac{\partial\theta_0}{\partial y} = -1, \frac{\partial\theta_1}{\partial y} = 0, \frac{\partial C_0}{\partial y} = -1, \frac{\partial C_1}{\partial y} = 0$$

$$\text{at } y = 0$$

$$u_0 \to 0,\ u_1 \to 0, \theta_0 \to 0,\ \theta_1 \to 0,$$

$$C_0 \to 0,\ C_1 \to 0 \ \text{ as } y \to \infty \tag{20}$$

Solving Eqs. (14- 19) under the boundary conditions (20) led to the following solutions.

$$C_0 = s_1 e^{-k_1 y} \tag{21}$$

$$\theta_0 = s_2 e^{-k_2 y} \tag{22}$$

$$u_0 = (-k_3 - k_4)e^{-l_1 y} + k_3 e^{-k_2 y} + k_4 e^{-k_1 y} \tag{23}$$

$$u_1 = k_{18}e^{-2k_2 y} + k_{19}e^{-2k_1 y} + k_{20}e^{-2l_1 y} + k_{21}e^{-l_2 y} + k_{22}e^{-l_3 y} + k_{23}e^{-l_4 y} + s_{12}e^{-l_6 y} + k_{25}e^{-k_1 y} - s_{13}e^{-l_7 y} \tag{24}$$

$$\theta_1 = k_{11}e^{-2k_2 y} + k_{12}e^{-2k_1 y} + k_{13}e^{-2l_1 y} + k_{14}e^{-l_2 y} + k_{15}e^{-l_3 y} + k_{16}e^{-l_4 y} + s_{11}e^{-l_6 y} \tag{25}$$

$$C_1 = 0 \tag{26}$$

$$\theta = s_2 e^{-k_2 y} + E\begin{pmatrix} k_{11}e^{-2k_2 y} + k_{12}e^{-2k_1 y} + k_{13}e^{-2l_1 y} + \\ k_{14}e^{-l_2 y} + k_{15}e^{-l_3 y} + k_{16}e^{-l_4 y} + s_{11}e^{-l_6 y} \end{pmatrix} \tag{27}$$

$$C = s_1 e^{-k_1 y} \tag{28}$$

$$u = (-k_3 - k_4)e^{-l_1 y} + k_3 e^{-k_2 y} + k_4 e^{-k_1 y} + E\begin{pmatrix} k_{18}e^{-2k_2 y} + k_{19}e^{-2k_1 y} + k_{20}e^{-2l_1 y} + k_{21}e^{-l_2 y} + k_{22}e^{-l_3 y} \\ + k_{23}e^{-l_4 y} + s_{12}e^{-l_6 y} + k_{25}e^{-k_1 y} - s_{13}e^{-l_7 y} \end{pmatrix} \tag{29}$$

3. 3. Skin-Friction Coefficient

In the velocity field, change rate of velocity at the plate in terms of skin friction is given in the non-dimensional form as follows:

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0} = (k_3 + k_4)l_1 - k_3 k_2 - k_4 k_1 + E(-2k_2 k_{18} - 2k_1 k_{19} - 2l_1 k_{20} - l_2 k_{21} - l_3 k_{22} - l_4 k_{23} - l_6 s_{12} - k_1 k_{25} e^{-k_1 y} + l_7 s_{13} \tag{30}$$

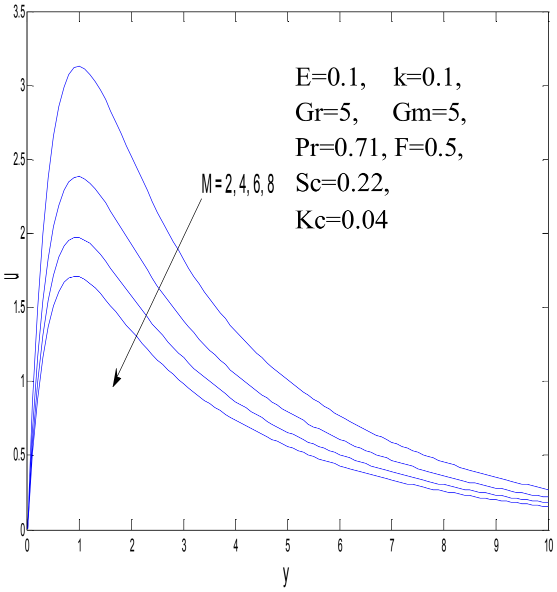

Fig. 1. Effect of M on velocity.

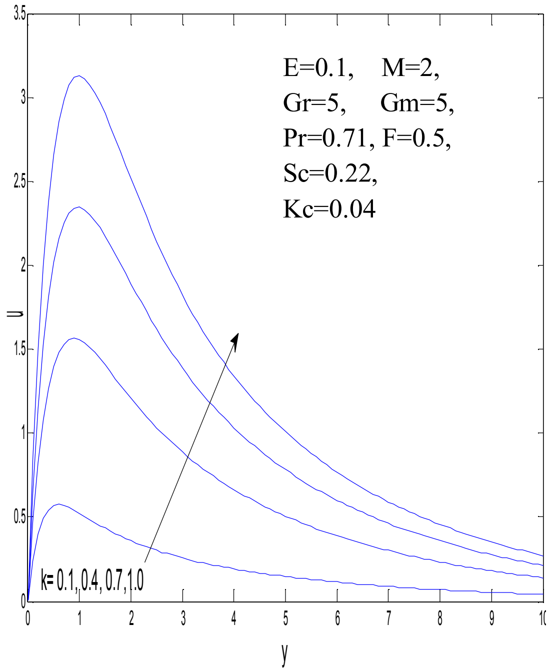

Fig. 2. Effect of permeability parameter k on velocity.

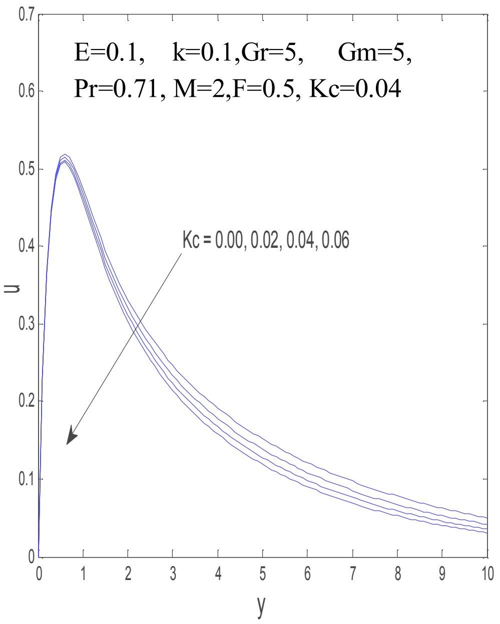

Fig. 3. Effect of chemical reaction parameter K_c on velocity.

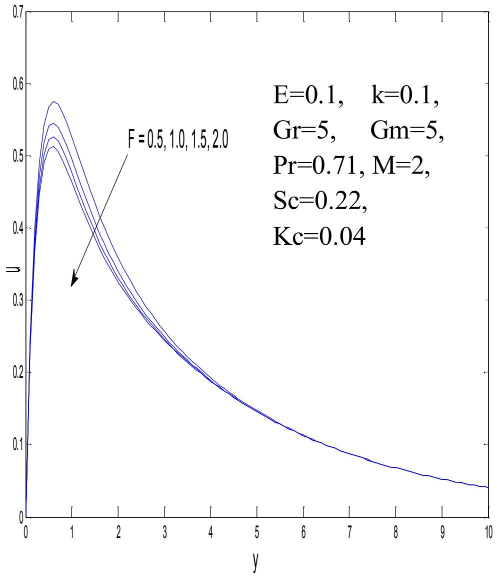

Fig. 4. Effect of radiation parameter F on velocity.

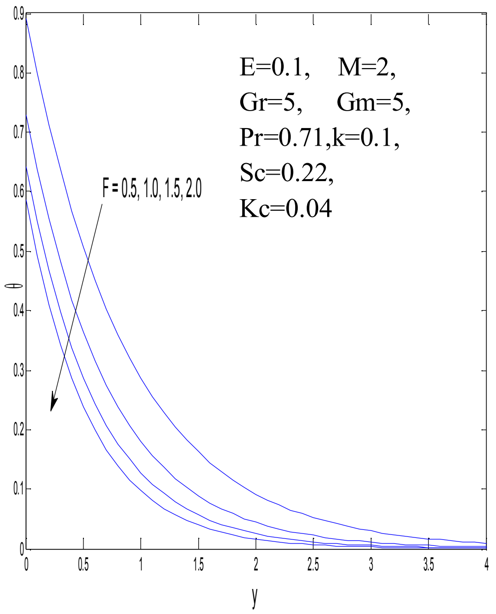

Fig. 5. Effect of radiation parameter F on temperature field.

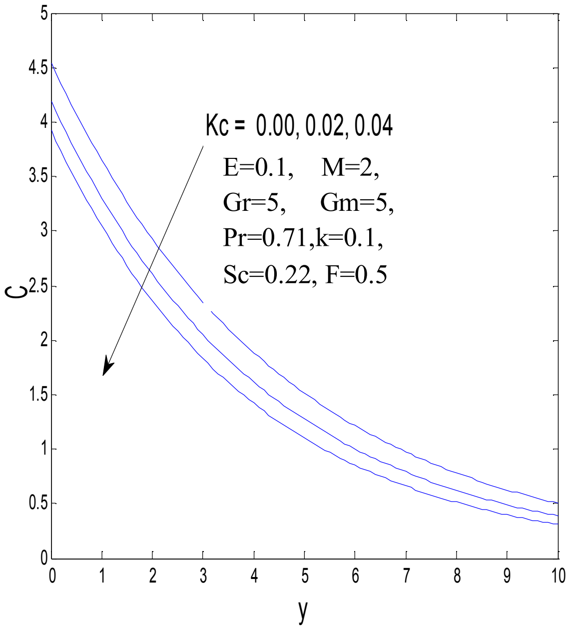

Fig. 6. Effect of chemical reaction parameter K_c on concentration field.

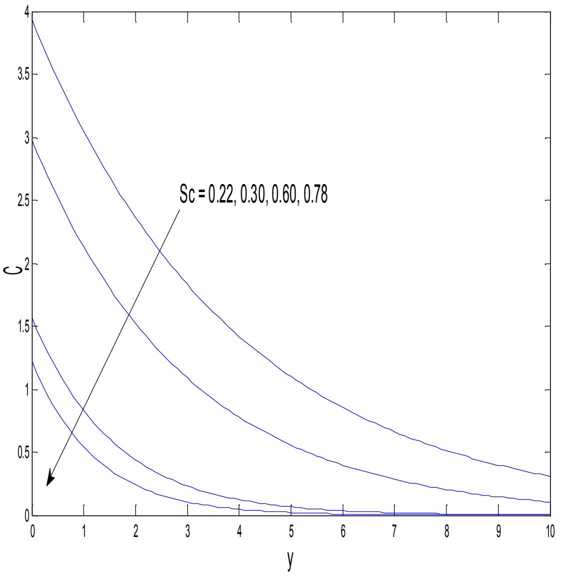

Fig. 7. Effect of Schmidt number S_c on concentration field.

Table 1. Effect of M, F, Kc and k on skin friction for E = 0.1, P_r=0.71, G_r= 5, G_m= 5.

M	F	K_c	k	Skin-friction
1	0.5	0.04	1	6.8127
2	0.5	0.04	1	5.3150
3	0.5	0.04	1	4.6208
2	1.0	0.04	1	5.0258
2	2.0	0.04	1	4.1860
2	0.5	0.00	1	5.2798
2	0.5	0.02	1	5.2984
2	0.5	0.04	0.7	4.9702
2	0.5	0.04	0.1	2.8311

4. Results and discussion

In order to get physical insight into the problem, velocity, temperature and concentration profiles were plotted for various values of physical parameters from Figs. 1- 7. Values of Prandtl number were chosen as P_r=7.0 (water) and P_r=0.71(air). The value of Schmidt number was chosen in such a way that it represented species by hydrogen (0.22), water vapor (0.60), ammonia (0.78), Ethyl benzene (2.01) and carbon dioxide (0.96). The results reported by Raju et al. [27] were not repeated here; but, effects of additional parameters were presented here. Effects of magnetic parameter M on velocity are shown in Fig. 1. It can be observed that, with the increase in M, velocity decrease. Physically, it meets the logic that the magnetic field extorts a retarding force on free convection flow which retards the flow. It can be also noticed that, near the plate in the vicinity of the boundary layer, velocity was considerably high and gradually and uniformly decreased thereafter. Effect of permeability parameter k is pointed out in Fig. 2. According to this figure, velocity increased with the increase of permeability of the porous medium. Effects of chemical reaction parameter K_c and radiation parameter F on flow transport are displayed in Figs. 3 and 4, respectively. From these figures, it can be observed that velocity decreased with the increase in chemical reaction parameter (K_c) or radiation parameter (F).

Effects of radiation parameter on temperature field are exhibited in Fig. 5. Accordingly, temperature decreased with increasing values of F. Concentration profiles for different values of chemical reaction parameter K_c and Schmidt parameter S_c are shown in Figs. 6 and 7, respectively, in which concentration increased with decreasing values of K_c or S_c. Finally, effects of various parameters like magnetic parameter M, radiation parameter F, permeability parameter k and chemical reaction parameter K_c on skin friction are presented in Table 1. It is interesting to note that skin friction was enhanced with the increase in values of K_c and k while it decreased with increasing values of magnetic parameter M and radiation parameter F.

5. Comparison of results

To compare results of this paper with those of Raju et al. [27], in the absence of magnetic field and chemical reaction, a set values of skin friction was chosen with variations in radiation parameter F and permeability parameter k. The results, which were found to be in good agreement with the existing results, are presented in the following table.

Table 2. Skin friction with variations in F and k when M=0 and Kc=0.

F	k	Results of Raju et al. [27] τ	Our results when M=0 and Kc=0 τ
0.5	1	4.6616	4.6602
1.0	1	3.7428	3.7422
0.5	0.7	3.5326	3.5321
0.5	0.1	1.8545	1.8540

6. Conclusions

In this paper, effect of radiation was considered on MHD free convection viscous dissipative past a moving vertical porous surface with chemical reaction. The non- dimensional governing equations were solved by series solution method. Conclusions of the study can be given as follows:

1. Velocity decreased with increased values of magnetic parameter M, radiation parameter F, chemical reaction parameter K_c or Prandtl number P_r.
2. Velocity increased as parameters of Grashof number G_r, modified Grashof number G_m, Eckert number E or porosity parameter k increased.
3. Temperature increased as permeability parameter k increased while decreasing with the increase of radiation parameter F.
4. Concentration decreased with increasing chemical reaction parameter K_c or Schmidt number Sc.

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