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RADIATION AND CHEMICAL REACTION EFFECTS ON MHD FLOW ALONG A MOVING VERTICAL POROUS PLATE

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This paper presents an analysis of the effects of magnetohydrodynamic force and buoyancy on convective heat and mass transfer flow past a moving vertical porous plate in the presence of thermal radiation and chemical reaction. The governing partial differential equations are reduced to a system of self-similar equations using the similarity transformations. The resultant equations are then solved numerically using the fourth order Runge-Kutta method along with the shooting technique. The results are obtained for the velocity, temperature, concentration, skin-friction, Nusselt number and Sherwood number. The effects of various parameters on flow variables are illustrated graphically, and the physical aspects of the problem are discussed.

Key words: MHD, porous medium, thermal radiation, heat and mass transfer, chemical reaction.

1. Introduction

Free convection arises in the fluid when temperature changes cause density variation leading to buoyancy forces acting on the fluid elements. In recent years, the problems of free convective heat and mass transfer flows through a porous medium under the influence of a magnetic field have attracted the attention of a number of researchers because of their possible applications in many branches of science and technology, such as applications in cooling of re-entry vehicles and rocket boosters, cross-hatching on ablative surfaces and film vaporization in combustion chambers. The simplest physical model of such a flow is the two dimensional laminar free convection flow along a vertical flat plate and various aspects of this type of flow have been investigated by many researchers such as Merkin [1], Lloyd and Sparrow [2], Wilks [3] and Raju *et al.* [4]. On the other hand, flows through a porous medium have numerous engineering and geophysical applications, for example, in chemical engineering for filtration and purification process; in agriculture engineering to study the underground water resources; in petroleum technology to study the movement of natural gas, oil and water through the oil reservoirs. In view of these applications, many researchers have studied MHD free convective heat and mass transfer flows in a porous medium; Raptis [5] investigated the flow through a porous medium in the presence of the magnetic field. The unsteady flow past

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a moving plate in the presence of free convection and radiation were presented by Mansour [6]. Raptis and Kafoussias [7] studied the magnetohydrodynamic free convection flow and mass transfer through a porous medium along an infinite vertical porous plate with constant heat flux. Sattar and Hossain [8] proposed the unsteady hydromagnetic free convection flow along an accelerated porous plate with time-dependent concentration in the presence of Hall current. Unsteady hydromagnetic free convection flow through a porous medium along an infinite vertical porous plate with constant heat flux with heat and mass transfer effects in the presence of variable suction was studied by Sattar [9]. Das *et al.* [10] studied the effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction. Abdus Sattar and Hamid Kalim [11] investigated the unsteady free convection interaction with thermal radiation in boundary layer flow past a vertical porous plate. Bakier and Gorla [12] studied thermal radiation effects on free convection from horizontal surfaces in a porous medium. Muthucumaraswamy [13] studied the effects of reaction on a moving isothermal vertical infinitely long surface with suction. Heat and mass transfer effect in MHD micropolar flow over a vertical porous plate was investigated by Kim [14]. Makinde [15] discussed radiation and mass transfer effects on free convection flow past a moving vertical porous plate. Chandrakala *et al.* [16] studied the same problem in the presence of a transverse magnetic field. The radiation effects on hydromagnetic flows were studied by Abdelkhalek [17]. Combined heat and mass transfer flow past a surface are analyzed by Chaudhary and Arpita [18].

The role of thermal radiation on the flow and heat transfer process is of major importance in the design of many advanced energy conversion systems operating at higher temperatures. Thermal radiation within these systems is usually the result of emission by hot walls and the working fluid. Radiation and mass transfer effects on a two-dimensional flow past an impulsively started isothermal vertical plate were analyzed by Ramachandra Prasad *et al.* [19]. Samad and Rahman [20] analysed the effect of radiation on unsteady MHD free convection flow past a vertical porous plate which is immersed in a porous medium. Heat and mass transfer effects on an unsteady MHD free convection flow of a rotating fluid past a vertical porous flat plate in the presence of thermal radiation was studied by Mbeledogu and Ogulu [21]. Radiation effects on an unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate embedded in a porous medium were studied by Prasad and Reddy [22]. Mostafa and Mahmoud [23] investigated the radiation effect on an unsteady MHD free convection flow past a vertical plate in the presence of temperature dependent viscosity. Ibrahim *et al.* [24] investigated the effects of chemical reaction on an unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate in the presence of heat generation, radiation and suction.

The study of magneto hydro-dynamics with mass and heat transfer in the presence of radiation has attracted the attention of a large number of scholars due to diverse applications. In astrophysics and geophysics, it is applied to study the stellar and solar structures, radio propagation through the ionosphere, etc. In engineering we find its applications in MHD pumps, MHD bearings, etc. The phenomenon of mass transfer is also very common in the theory of stellar structure and observable effects are detectable on the solar surface.

The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. Possible applications of this type of flow can be found in many industries such as the power industry and chemical process industries. In many chemical engineering processes, there does occur the chemical reaction between a foreign mass and the fluid in which the plate is moving. These processes take place in numerous industrial applications viz., polymer production, manufacturing of ceramics or glassware and food processing. Mohammed Nasser El-Fayez [25] analyzed the chemical reaction effects on an unsteady free convection flow past an infinite vertical permeable moving plate with variable temperature. An unsteady MHD convective heat and mass transfer past an infinite vertical plate embedded in a porous medium with radiation and chemical reaction under the influence of Dufour and Soret effects was investigated by Mohammed Ibrahim [26]. Chemical reaction and radiation effects on an unsteady MHD heat and mass transfer flow past a moving inclined porous heated plate were studied by Uddin and Kumar [27].

Hence, the objective of this paper is to study the effect of thermal radiation on an MHD free convection flow along a moving vertical porous plate in the presence of thermal radiation and chemical reaction of first-order. The governing equations are transformed by using unsteady similarity transformation and the resultant dimensionless equations are solved numerically using the shooting technique. The effects of various governing parameters on the velocity, temperature, concentration are obtained.

2. Mathematical analysis

Consider an unsteady two-dimensional free convection flow of a viscous incompressible electrical conducting, thermal radiating and chemical reacting fluid along a moving vertical porous plate immersed in a porous medium. The x-axis is taken along the plate in the upward direction and the y-axis is taken normal to the plate. The fluid is considered to be a gray, absorbing emitting radiation but non-scattering medium and the Rosseland approximation is used to describe the radiation heat flux in the energy equation. A uniform magnetic field is applied in the direction perpendicular to the plate. The fluid is assumed to be slightly conducting, and hence the magnetic Reynolds number is much less than unity and the induced magnetic field is negligible in comparison with the applied magnetic field. It is assumed that the external electrical field is zero and the electric field due to the polarization of charges is negligible. Initially, the plate and the fluid are at the same temperature T_∞ and the concentration C_∞. At time $t > 0$, the plate temperature and concentration are raised to T_w and C_w respectively and are maintained constant thereafter. It is also assumed that all fluid properties are constant except the influence of the density variation with temperature and concentration in the body force term (Boussinesq's approximation). Also, there is a chemical reaction between the diffusing species and the fluid. The foreign mass present in the flow is assumed to be at low level and hence Soret and Dufour effects are negligible. Under these assumptions, the governing boundary layer equations of the flow field are:
Conservation of mass

$$\frac{\partial v}{\partial y} = 0 . \tag{2.1}$$

Conservation of momentum

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + g\beta\left(T - T_\infty\right) + g\beta^*\left(C - C_\infty\right) - \frac{\sigma B_0^2}{\rho}u - \frac{\nu}{K^*}u . \tag{2.2}$$

Conservation of energy (Heat)

$$\rho c_p\left(\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial y^2} - \frac{\partial q_r}{\partial y} . \tag{2.3}$$

Conservation of species (Concentration)

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - Kr^*\left(C - C_\infty\right) \tag{2.4}$$

where u and v are the velocity components in x and y directions, respectively, ρ -the fluid density, g -the acceleration due to gravity, β, β^* -the thermal and concentration expansion coefficients respectively, T -the temperature of the fluid in the boundary layer, ν -the kinematic viscosity, σ-the electrical conductivity of the fluid, T_∞ -the temperature of the fluid far away from the plate, α -the thermal diffusivity, C -the species concentration in the boundary layer, C_∞ -the species concentration in fluid far away from the plate, B_0 -the magnetic induction, k -the thermal conductivity, q_r -the local radiative heat flux and D -the mass diffusivity and Kr^* -the chemical reaction parameter. The second and third terms on the right hand side of the momentum Eq.(2.2) denote the thermal and concentration buoyancy effects, respectively.

The boundary conditions for the velocity, temperature and concentration fields are

$$\begin{gathered} t \le 0 : u = 0, \quad v = 0, \quad T = T_\infty, \quad C = C_\infty \quad \text{for all} \quad y, \\ t > 0 : \begin{cases} u = U, \quad v = v(t), \quad T = T_w, \quad C = C_w \quad \text{at} \quad y = 0, \\ u \to 0, \quad v \to 0, \quad T = T_\infty, \quad C = C_\infty \quad \text{as} \quad y \to \infty. \end{cases} \end{gathered} \tag{2.5}$$

where U is the plate characteristic velocity.

Thermal radiation is assumed to be present in the form of a unidirectional flux in the y - direction i.e., q_r (Transverse to the vertical surface). By using the Rosseland approximation [28] the radiative heat flux q_r is given by

$$q_r = -\frac{4\sigma_s}{3k_e}\frac{\partial T^4}{\partial y}. \tag{2.6}$$

It should be noted that by using the Rosseland approximation, the present analysis is limited to optically thick fluids. If temperature differences within the flow are sufficiently small, then Eq.(2.6) can be linearized by expanding T^4 in Taylor series about T_∞ which after neglecting higher order terms takes the form

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4. \tag{2.7}$$

In view of Eqs (2.6) and (2.7), Eq.(2.3) reduces to

$$\rho c_p\left(\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma_s}{3k_e}T_\infty^3\frac{\partial^2 T}{\partial y^2} + Q_0\left(T - T_\infty\right). \tag{2.8}$$

We introduce similarity variables and the dimensionless quantities, i.e.,

$$\begin{gathered} \eta = \frac{y}{2\sqrt{\nu t}}, \quad u = Uf(\eta), \quad \theta = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi = \frac{C - C_\infty}{C_w - C_\infty}, \\ \mathrm{Gc} = \frac{4g\beta^*\left(C_w - C_\infty\right)t}{U}, \quad \mathrm{Gr} = \frac{4g\beta\left(T_w - T_\infty\right)t}{U}, \\ M = \frac{4\sigma B_0^2 t}{\rho}, \quad K^* = \frac{K\nu}{tc}, \quad R = \frac{16\sigma_s\left(T_w - T_\infty\right)^3}{3k_e k}, \\ N = \frac{T_\infty}{T_w - T_\infty}, \quad \mathrm{Pr} = \frac{\mu c_p}{k}, \quad \mathrm{Sc} = \frac{\nu}{D}, \quad Kr^* = \frac{Kr}{4t}. \end{gathered} \tag{2.9}$$

From Eq.(2.1), v is either a constant or a function of time. Following (Singh and Soundalgekar [29]), we choose

$$v = -c\left(\frac{\nu}{t}\right)^{\frac{1}{2}} \tag{2.10}$$

where $c > 0$ is the suction parameter.

In view of Eqs (2.9) and (2.10), Eqs (2.2), (2.8) and (2.4) reduce to

$$f'' + 2(\eta + c)f' + \mathrm{Gr}\theta + \mathrm{Gc}\phi - \left(M + \frac{1}{K}\right)f = 0, \tag{2.11}$$

$$\theta'' + 2(\eta + c)\mathrm{Pr}\theta' + R\left(3(N+\theta)^2\theta'^2 + (N+\theta)^3\theta''\right) = 0, \tag{2.12}$$

$$\phi'' + 2(\eta + c)\mathrm{Sc}\phi' - Kr\mathrm{Sc}\phi = 0 \tag{2.13}$$

where the primes denote the differentiation with respect to η, M is the magnetic field parameter, Pr is the Prandtl number, Sc is the Schmidt number, Gr is the thermal Grashof number, Gc is the modified Grashof number, R is the radiation parameter, N is the temperature difference parameter and Kr is the chemical reaction parameter.

The corresponding dimensionless boundary conditions are

$$\begin{cases} f = 1, \quad \theta = 1, \quad \phi = 1, & \text{at } \eta = 0, \\ f \to 0, \quad \theta \to 0, \quad \phi \to 0 & \text{as } \eta \to \infty. \end{cases} \tag{2.14}$$

3. Solution of the problem

The set of coupled non-linear governing boundary layer Eqs (2.11)-(2.13) together with the boundary conditions (2.14) are solved numerically by using the Runge-Kutta fourth order technique along with the shooting method. First of all, higher order non-linear differential Eqs (2.11)-(2.13) are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem by applying the shooting technique [30-31]. The resultant initial value problem is solved by employing the Runge-Kutta fourth order technique. The step size $\Delta\eta = 0.005$ is used to obtain the numerical solution with the sixth decimal place accuracy as the criterion of convergence.

4. Results and discussion

The problem of an unsteady MHD free convection fluid flow past a moving vertical porous plate embedded in porous medium with thermal radiation and chemical reaction in the presence of suction has been considered. The numerical values of velocity (*f*), temperature (θ) and concentration (ϕ) with the boundary layer have been computed for different parameters as the thermal Grashof number Gr, solutal Grashof number Gc, magnetic field parameter *M*, permeability parameter *K*, Prandtl number Pr, thermal radiation parameter *R*, Schmidt number Sc and suction parameter, *c*. In the present study we adopted the following default parametric values: Gr = 10, Gc = 6, $M = 1.0$, $K = 0.5$, Pr = 0.71, $R = 0.5$, $N = 0.1$, Sc = 0.6, *Kr = 0.5*, *c = 0.5*. All the graphs therefore correspond to these values unless specifically indicated on the appropriate graph.

The influence of the thermal Grashof number Gr on velocity is shown in Fig.1. The flow is accelerated due to the enhancement in buoyancy force corresponding to an increase in the thermal Grashof number, i.e., free convection effects. The positive values of Gr correspond to cooling of the plate by natural convection. Heat is therefore conducted away from the vertical plate into the fluid which increases the temperature and thereby enhances the buoyancy force. In addition, it is seen that the peak values of the velocity increases rapidly near the plate as the thermal Grashof number increases and then decays smoothly to the free stream velocity.

Figure 2 presents typical velocity profiles in the boundary layer for various values of the solutal Grashof number Gc. It is noticed that the velocity increases with increasing values of the solutal Grashof number. The effect of the magnetic field parameter *M* on the velocity is shown in Fig.3. The velocity decreases with an increase in the magnetic field parameter. It is because the application of the transverse magnetic field will result in a resistive type force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reduces its velocity. Also, the boundary layer thickness decreases with an increase in the magnetic parameter. Figure 4 shows the effects of the permeability parameter on the velocity profiles. From this figure it is seen that velocity increases with an increase of the permeability parameter *K*.

Figures 5 and 6 illustrate the velocity and temperature profiles for different values of the Prandtl number Pr. The numerical results show that the increasing values of the Prandtl number result in a decreasing velocity. From Fig.5, it is observed that an increase in the Prandtl number results in a decrease of the thermal boundary layer thickness and in a generally lower average temperature within the boundary layer. The reason is that smaller values of Pr are equivalent to increasing the thermal conductivities, and therefore heat is able to diffuse away from the heated surface more rapidly than for higher values of Pr. Hence in the case of smaller Prandtl numbers the boundary layer is thicker and the rate of heat transfer is reduced.

The influence of the thermal radiation parameter *R* on the velocity and temperature is shown in Figs 7 and 8, respectively. It is obvious that an increase in the radiation parameter *R* results in an increase in both the velocity and temperature within the boundary layer. Figures 9 and 10 illustrate the velocity and temperature profiles for different values of the temperature difference parameter *N*. It is seen that the increasing values of *N* result in increasing both the velocity and temperature profiles. Figures 11 and 12 show the velocity and concentration profiles for different values of the chemical reaction parameter *Kr*. It is observed that an increase in the chemical reaction parameter *Kr* results in a decrease in both the velocity and concentration. Figures 13, 14 and 15 show the velocity, temperature and concentration profiles for different values of the suction parameter *c*. It is observed that an increase in the suction parameter *c* results in a decrease in the velocity, temperature and concentration.

For different values of the Schmidt number Sc, the velocity and concentration profiles are plotted in Figs 16 and 17, respectively. It physically relates the relative thickness of the hydrodynamic boundary layer and mass transfer (concentration) boundary layer. As the Schmidt number Sc increases the concentration decreases. This causes the concentration buoyancy effects to decrease yielding a reduction in the fluid velocity. The reductions in the velocity and concentration profiles are accompanied by a simultaneous reductions in the velocity and concentration boundary layers, which is evident from Figs 16 and 17.

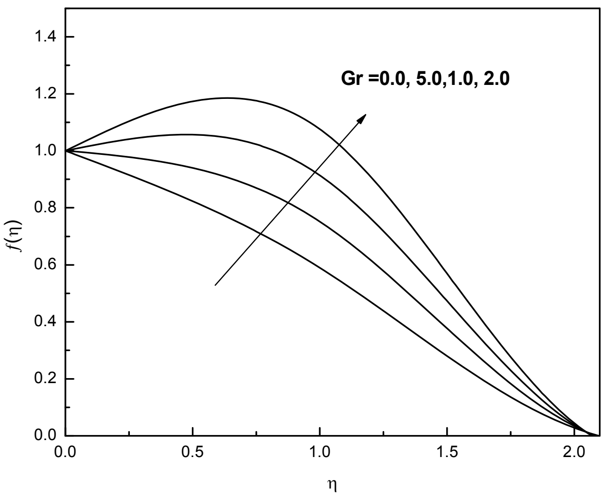


Fig.1. Velocity profiles for different values of Gr.

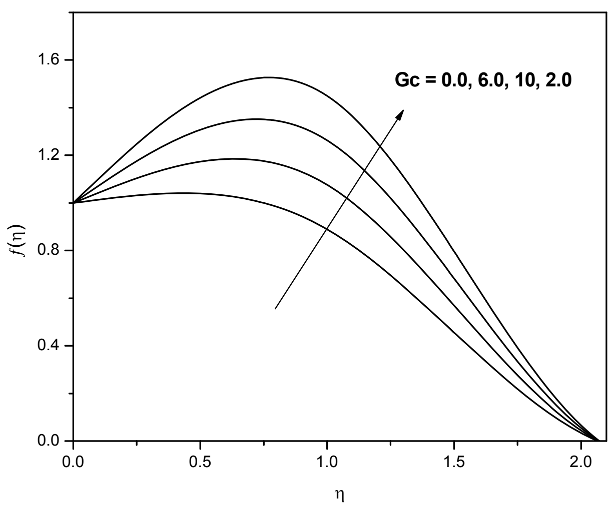


Fig.2. Velocity profiles for different values of Gc.

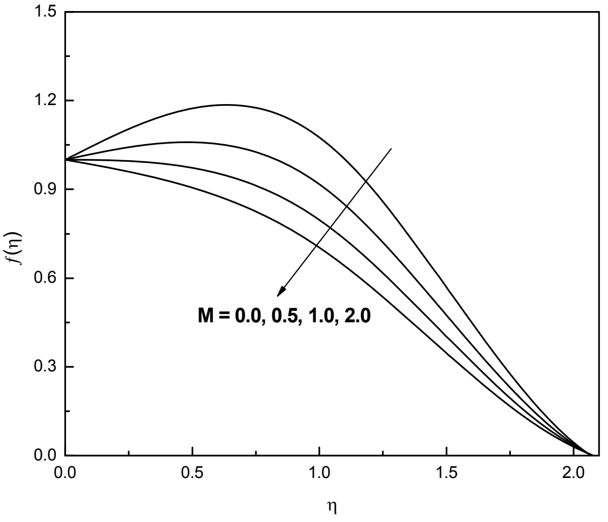


Fig.3. Velocity profiles for different values of *M.*

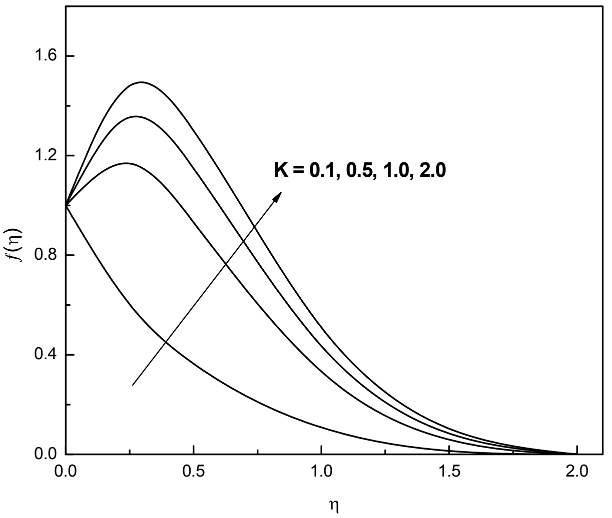


Fig.4. Velocity profiles for different values of *K.*

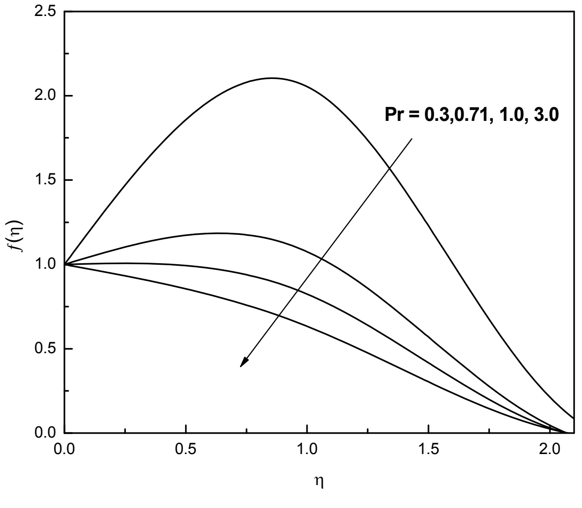


Fig.5. Velocity profiles for different values of Pr.

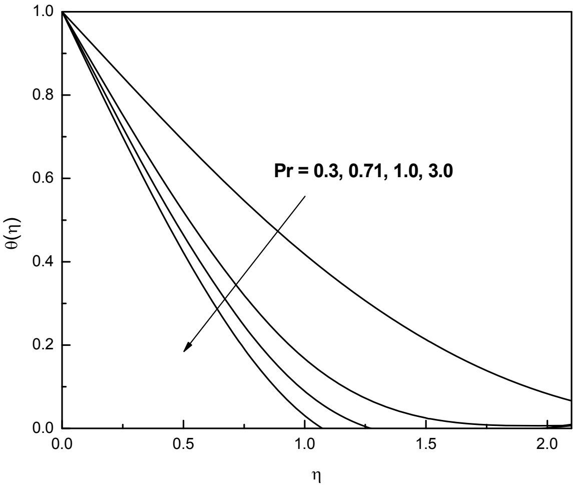
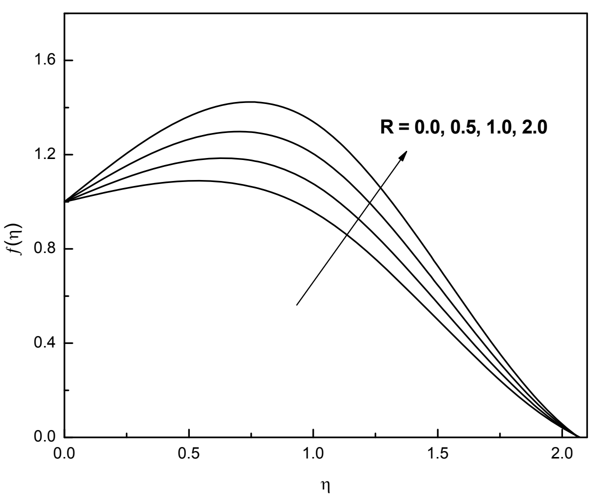


Fig.6. Temperature profiles for different values of Pr.



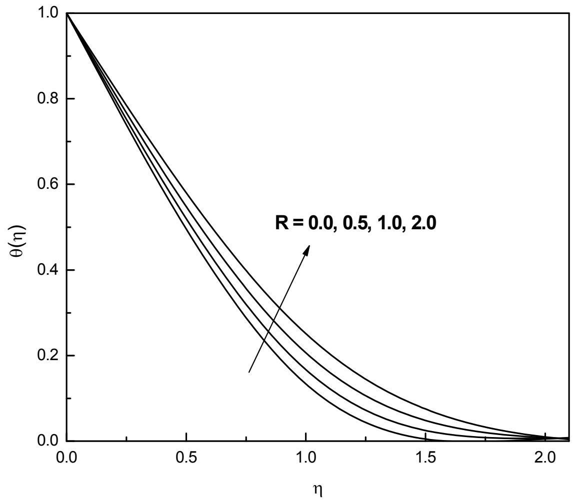
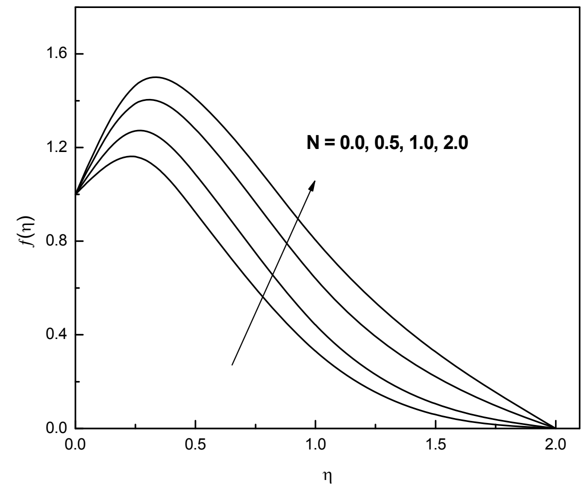


Fig.7. Velocity profiles for different values of *R*.

Fig.8. Temperature profiles for different values of *R*.



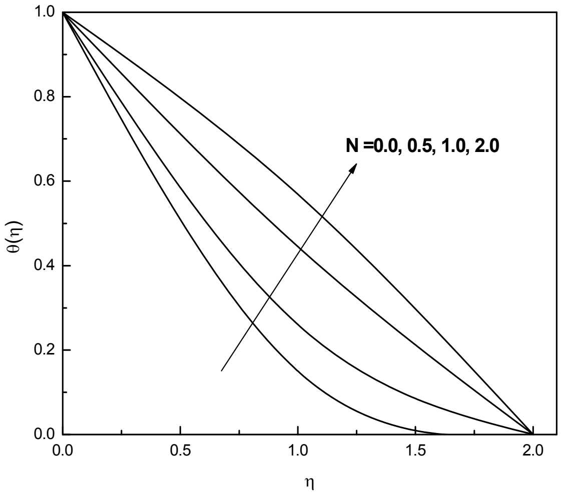
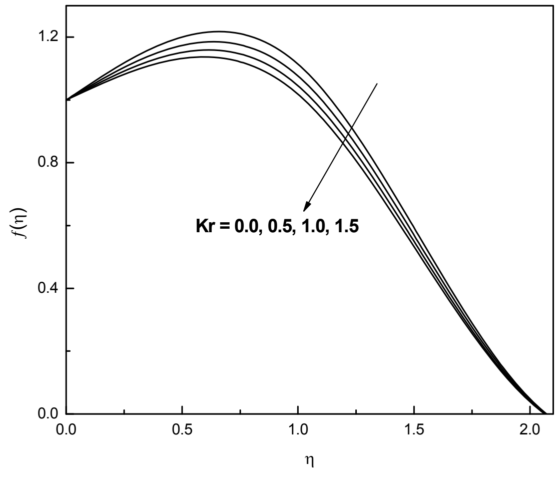


Fig.9. Velocity profiles for different values of *N*.

Fig.10. Temperature profiles for different values of *N*.



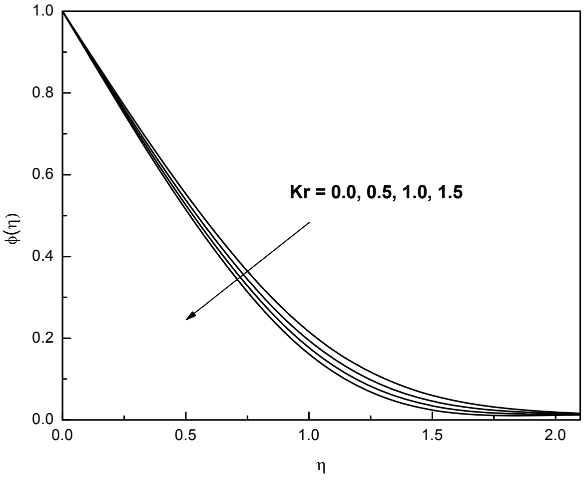


Fig.11. Velocity profiles for different values of *Kr*.

Fig.12. Concentration profiles for different values of *Kr*.

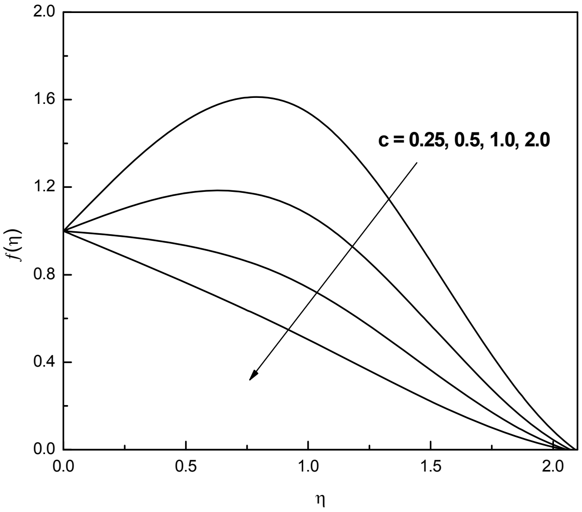


Fig.13. Velocity profiles for different values of *c*.

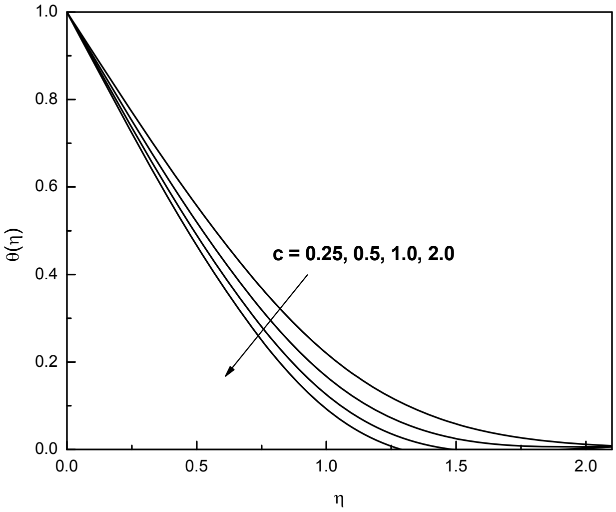


Fig.14. Temperature profiles for different values of *c*.

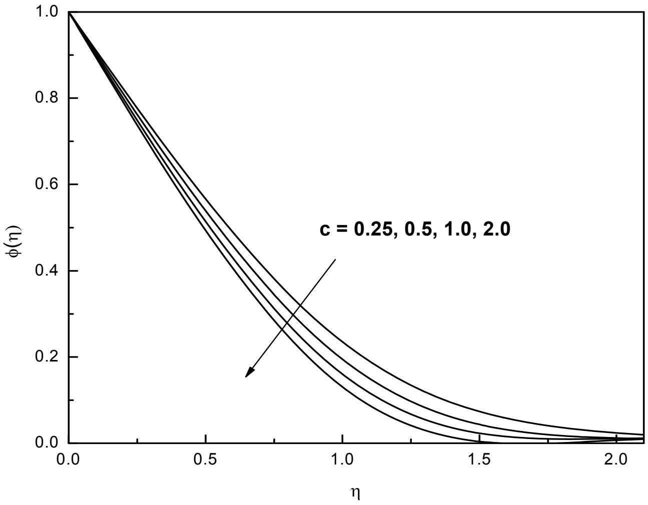


Fig.15. Concentration profiles for different values of *c*.

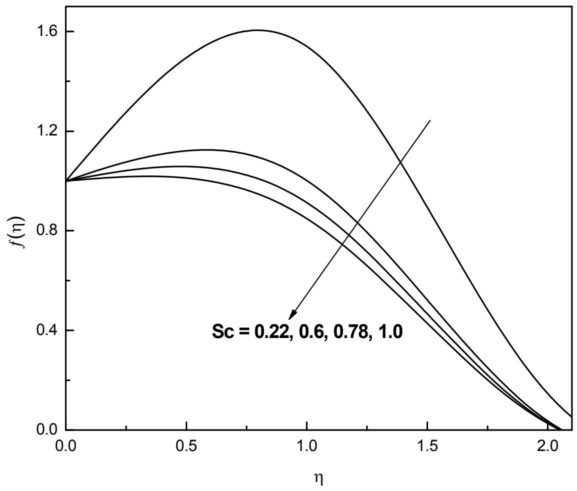


Fig.16. Velocity profiles for different values of Sc.

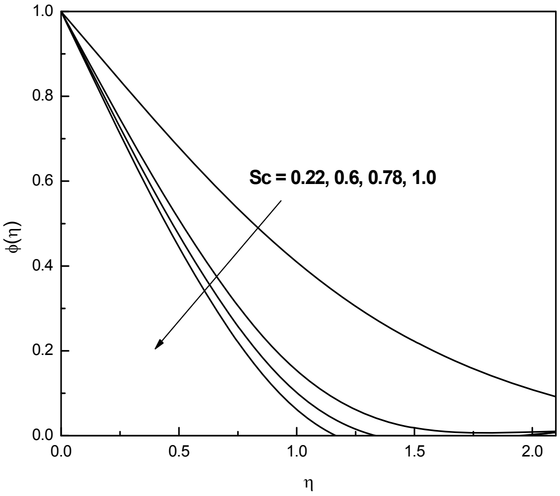


Fig.17. Concentration profiles for different values of Sc.

5. Conclusions

In this paper the thermal radiation effects on an unsteady MHD free convection flow through a moving vertical porous plate embedded in a porous medium are studied. The expressions for the velocity, temperature, and concentration distributions which are the equations governing the flow are numerically solved by the fourth-order Runge-Kutta method along with the shooting technique. The magnetic field has a significant effect on the velocity field and retards the motion of the fluid. Radiation has significant effects on the velocity as well as temperature distributions, i.e., velocity and temperature profiles increase with the increase of thermal radiation. Using suction boundary layer growth can be controlled. Suction stabilizes the hydrodynamic, thermal as well as concentration boundary layers growth.

Nomenclature

B_0 – magnetic induction, k- thermal conductivity
C – species concentration in the boundary layer
C_∞ – species concentration in the fluid far away from the plate
D – mass diffusivity
Gc – modified Grashof number
Gr – thermal Grashof number
g – acceleration due to gravity
Kr – chemical reaction parameter
Kr^* – chemical reaction parameter
M – magnetic field parameter
N – temperature difference parameter
Pr – Prandtl number
q_r – local radiative heat flux
R – radiation parameter
Sc – Schmidt number
T – temperature of the fluid in the boundary layer
T_∞ – temperature of the fluid far away from the plate
U – plate characteristic velocity
u, v – velocity components in x and y directions, respectively
α – thermal diffusivity
β, β^* – thermal and concentration expansion coefficients, respectively
ν – kinematic viscosity
ρ – fluid density
σ – electrical conductivity of the fluid

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