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Research Article

MHD Flow past a Moving Vertical Porous Plate in The Presence of Radiation and Chemical Reaction Effects

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ABSTRACT

Aim of the paper is to investigate the radiation effect on an unsteady magneto hydrodynamic free convective heat and mass transfer flow past a moving vertical porous plate embedded in a porous medium in the presence of chemical reaction is analyzed. 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 shooting technique. The effects of governing physical parameters on velocity, temperature and concentration as well as skin-friction coefficient, Nusselt number and Sherwood number are computed and presented in graphical and tabular forms. Comparisons with previously published work are performed and the results are found to be in excellent agreement.

Keywords:- Unsteady MHD, Porous medium, Thermal radiation, Heat and mass transfer, chemical reaction, convection.

1. INTRODUCTION

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 been attracted the attention of a number of researchers because of their possible applications in many branches of science and technology, such as its applications in transportation 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 flows 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, flow 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 flow in a porous medium; Raptis [5] investigated the flow through a porous medium in presence of magnetic field. Combined heat and mass transfer flow past a surface are analyzed by Chaudhary and Arpita. [6]. Raptis and Kafoussias [7] studied the magnetohydrodynamic free convection flow and mass transfer past through a porous medium along an infinite vertical porous plate with constant heat flux. 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 presence of variable suction was studied by Sattar [8]. Heat and mass transfer effect in MHD micropolar flow over a vertical porous plate has been investigated by Kim [9]. Sattar and Hossain [10] proposed the unsteady hydromagnetic free convection flow along an accelerated porous plate with time-dependent and concentration in presence of hall current.

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. The unsteady flow past a moving plate in the presence of free convection and radiation were presented by Mansour [11]. Radiation and mass transfer effects on two-dimensional flow past an impulsively started isothermal vertical plate were analyzed by Ramachandra Prasad *et al.*[12]. Abdus Sattar and Hamid kalim [13] investigated the unsteady free convection interaction with thermal radiation in boundary layer flow past a vertical porous plate. Makinde [14] discussed radiation and mass transfer effects on free convection flow past a moving vertical porous plate.

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 like in MHD pumps, MHD bearings, etc. The phenomenon of mass transfer is also very common in theory of stellar structure and observable effects are detectable on the solar surface. In free convection flow the study of effects of magnetic field play a major rule in liquid metals, electrolytes and ionized gases. In power engineering, the thermal physics of hydro magnetic problems with mass transfer have enormous applications. Raptis and Pedikis [15] analysed the effect ofthermal radiation and free convection flow past a moving plate. Chandrakala et al. [16] studied the same problem in the presence of transverse magnetic field. The radiation effect on hydromagnetic flows was studied by Abdelkhalek [17]. Bakier and Gorla [18] studied thermal radiation effects on free convection from horizontal surfaces in porous medium. 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 was studied by Prasad and Reddy [19]. Heat and mass transfer effects on an unsteady MHD free convection flow of rotating fluid past a vertical porous flat plate in the presence of thermal radiation has been studied by Mbeledogu and Ogulu [20]. Mostafa et al. [21] found the radiation effect on unsteady MHD free convection flow past a vertical plate in presence of temperature dependent viscosity. Samad and Rahman [22] proposed the effect of radiation on unsteady MHD free convection flow past a vertical porous plate which is immersed in a porous medium.

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 like 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. Das *et al.*[23] studied the effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction. Muthucumaraswamy [24] has studied the effects of reaction on a moving isothermal vertical infinitely long surface with suction. Mohammed Nasser El-Fayez [25] analyzed the chemical reaction effects on unsteady free convection flow past an infinite vertical permeable moving plate with variable temperature. Ibrahim et al. [26] investigated the effects of chemical reaction on unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate in presence of heat generation, radiation and suction. 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 has been investigated by Mohammed Ibrahim [27]. Chemical reaction and radiation effects on unsteady MHD heat and mass transfer flow past through a moving inclined porous heated plate was studied by Ziya Uddin and Manoj Kumar [28].

In spite of all these studies, the unsteady MHD free convection heat and mass transfer flow past a moving vertical porous plate immersed in a porous medium in presence of chemical reaction and radiation has received a little attention. Hence, the aim of the present study is to investigate the effect of thermal radiation on MHD free convection flow past along a moving vertical porous plate embedded in porous plate in presence of chemical reaction of first-order. The governing equations are transformed by using unsteady similarity transformation and the resultant dimensionless equations are solved numerically using shooting technique. The effects of various governing parameters on the velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number 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 flow along a moving vertical porous plate immersed in a porous medium. The *x*-axis is taken along the plate in the upward direction and *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 constantly thereafter. It is also assumed that all fluid properties are constant except that the influence of the density variation with temperature and concentration in the body force term (Boussinesq's approximation). Also, there is 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:

$$\frac{\partial v}{\partial y} = 0 \qquad (1)$$

Conservation of momentum:

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

Conservation of energy (Heat):

$$\rho c_p\left(\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial y}\right)=k\frac{\partial^2 T}{\partial y^2}-\frac{\partial q_r}{\partial y} \quad (3)$$

Conservation of species (Concentration):

$$\frac{\partial C}{\partial t}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-Kr^*\left(C-C_\infty\right) \quad (4)$$

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 equation (2) denote the thermal and concentration buoyancy effects respectively.

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

$t\le 0:\ \ u=0,\ \ v=0,\ \ T=T_\infty,\ \ C=C_\infty;$ for all y

$t>0:\ u=U,\ v=v(t),\ T=T_w,\ C=C_w$ at y = 0 $u\to 0, v\to 0, T=T_\infty, C=C_\infty$ as $y\to\infty$. (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 [29] the radiative heat flux q_r is given by

$$q_r=-\frac{4\sigma_s}{3k_e}\frac{\partial T^4}{\partial y} \quad (6)$$

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 equation (6) can be linear zed by expanding T^4 in Taylor series about T_∞ which after neglecting higher order terms takes the form:

$$T^4\approx 4T_\infty^3 T-3T_\infty^4 \quad (7)$$

In view of equations (6) and (7), equation (3) reduces to:

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

(8)

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

$$\eta=\frac{y}{2\sqrt{\nu t}},\ u=Uf(\eta),\theta=\frac{T-T_\infty}{T_w-T_\infty},$$

$$\phi=\frac{C-C_\infty}{C_w-C_\infty},$$

$$Gr=\frac{4g\beta\left(T_w-T_\infty\right)t}{U},\ Gc=\frac{4g\beta^*\left(C_w-C_\infty\right)t}{U},$$

$$M=\frac{4\sigma B_0^2 t}{\rho},\ K^*=\frac{K\nu}{tc}\ \ R=\frac{16\sigma_s\left(T_w-T_\infty\right)^3}{3k_e k},$$

$$N=\frac{T_\infty}{T_w-T_\infty},\Pr=\frac{\mu c_p}{k},Sc=\frac{\nu}{D},Kr^*=\frac{Kr}{4t}$$

(9)

From equation (1), v is either a constant or a function of time. Following (Singh and Soundalgekar [30]), we choose

$$v=-c\left(\frac{\nu}{t}\right)^{\frac{1}{2}} \quad (10)$$

where $c>0$ is the suction parameter.

in view of equations (9) and (10), the equations (2), (8) and (4) reduce to

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

(11)

$$\theta''+2(\eta+c)\Pr\theta'+R\left(3(N+\theta)^2\theta'^2+(N+\theta)^3\theta''\right)=0$$

(12)

$$\phi''+2(\eta+c)Sc\phi'-KrSc\phi=0 \quad (13)$$

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 radiation parameter, N is the temperature difference parameter and Kr is the chemical reaction parameter.

The corresponding dimensionless boundary conditions are

$$f = 1,\ \theta = 1, \phi = 1, \text{ at } \eta = 0$$

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

3. Skin-Friction Coefficient, Nusselt Number and Sherwood Number:

For the flow under consideration, the physical quantities such as the wall shear stress, surface heat flux and the surface mass flux are very important and these are given by

$$\tau_w = \mu \left(\frac{\partial u}{\partial y} \right)_{y=0} \quad (15)$$

$$q_w = -k \left(\frac{\partial T}{\partial y} \right)_{y=0} \quad (16)$$

$$M_w = -D \left(\frac{\partial C}{\partial y} \right)_{y=0} \quad (17)$$

where μ - is the viscosity and *k*- the thermal conductivity.

Hence, the skin-friction coefficient, Nusselt number and Sherwood number near the plate are given by

$$C_f = \frac{2\tau_w}{\rho U \sqrt{\nu t}} = \frac{2\mu}{\rho U \sqrt{\nu t}} \left(\frac{\partial u}{\partial y} \right)_{y=0} = 2 \operatorname{Re}^{-1} f'(0) \quad (18)$$

$$Nu = \frac{2 q_w \sqrt{\nu t}}{k(T_w - T_\infty)} = -\frac{2k\sqrt{\nu t}}{k(T_w - T_\infty)} \left(\frac{\partial T}{\partial y} \right)_{y=0} = -\theta'(0) \quad (19)$$

$$Sh = \frac{2M_w\sqrt{\nu t}}{D(C_w - C_\infty)} = -\frac{2D\sqrt{\nu t}}{D(C_w - C_\infty)} \left(\frac{\partial C}{\partial y} \right)_{y=0} = -\phi'(0) \quad (20)$$

where $\operatorname{Re} = \frac{Ut}{\nu}$ is the Reynolds number.

4. Solution of the Problem

The set of coupled non-linear governing boundary layer equations (11)-(13) together with the boundary conditions (14) are solved numerically by using Runge-Kutta fourth order technique along with shooting method. First of all, higher order non-linear differential Equations (11)-(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 (Conte and Boor [31], Jain *et al*., [32]). The resultant initial value problem is solved by employing Runge-Kutta fourth order technique. The step size $\Delta\eta = 0.005$ = 0.05 is used to obtain the numerical solution with decimal place accuracy as the criterion of convergence. From the process of numerical computation, the skin-friction coefficient, the Nusselt number and the Sherwood number, which are respectively proportional to $f'(0), -\theta'(0)$ and $-\phi'(0)$, are also sorted out and their numerical values are presented in a tabular form.

5. RESULTS AND DISCUSSION

The problem considering for unsteady MHD free convection fluid flow past a moving vertical porous plate embedded in porous medium with thermal radiation and chemical reaction in presence of suction. 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 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 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 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 that the application of transverse magnetic field will result a resistive type force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity. Also, the boundary layer thickness decreases with an increase in magnetic parameter. Figure 4 shows the effects of permeability parameter on the velocity profiles. From this figure it is seen that velocity increase with an increase of permeability parameter *K*.

Figure 5 and 6 illustrate the velocity and temperature profiles for different values of Prandtl number *Pr*. The numerical results show that the effect of increasing values of Prandtl number results 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 general 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 as 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 are 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 temperature difference parameter *N*. It is seen that the effect of increasing values of *N* results in increasing both velocity and temperature profiles.

For different values of the Schmidt number *Sc*, the velocity and concentration profiles are plotted in Figs.11 and 12 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 simultaneous reductions in the velocity and concentration boundary layers, which is evident from Figs. 11 and 12.

Figures 13 and 14 show the velocity and concentration profiles for different values of 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 15, 16 and 17 show the velocity, temperature and concentration profiles for different values of suction parameter *c*. it is observed that an increase in the suction parameter *c* results in a decrease in the velocity, temperature and concentration.

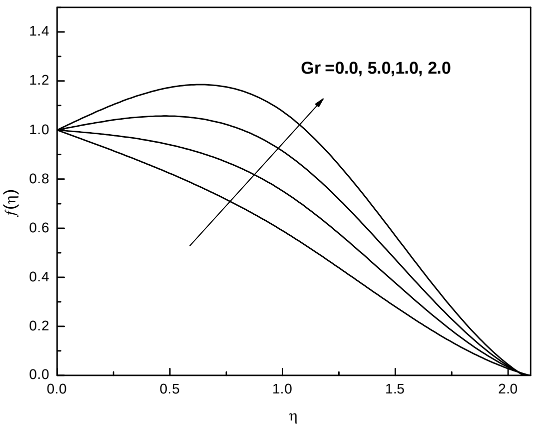

Fig. 1: Velocity Profiles for Different Values of *Gr*

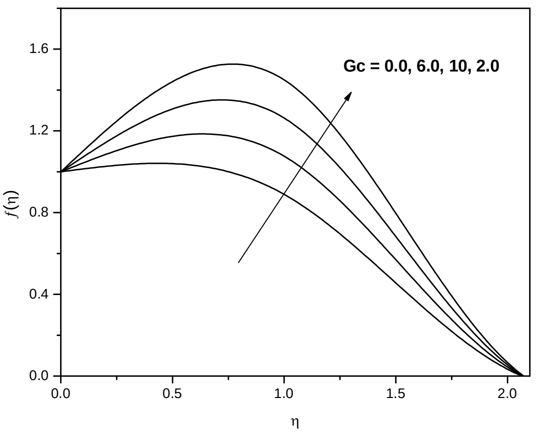

Fig. 2: Velocity Profiles for Different Values of *Gc*

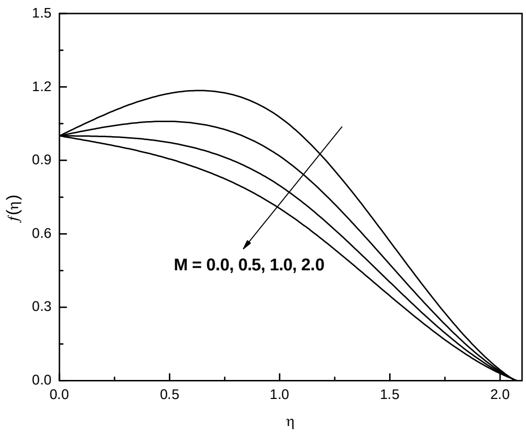

Fig. 3: Velocity Profiles for Different Values of *M*

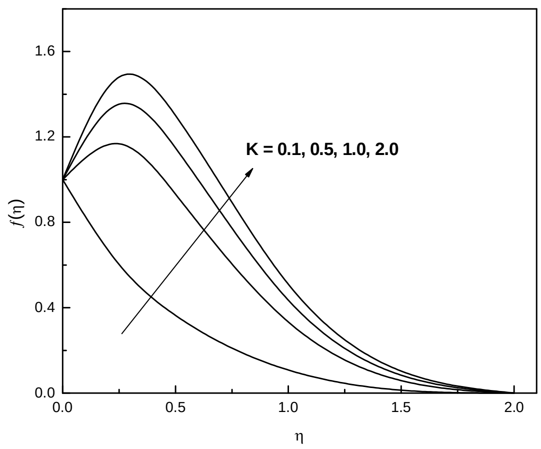

Fig. 4: Velocity Profiles for Different Values of *K*

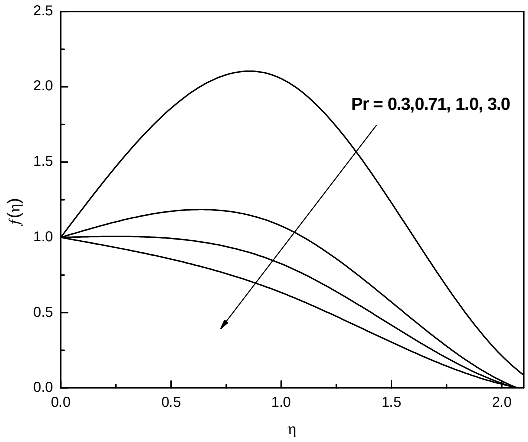

Fig. 5: Velocity Profiles for Different Values of *Pr*

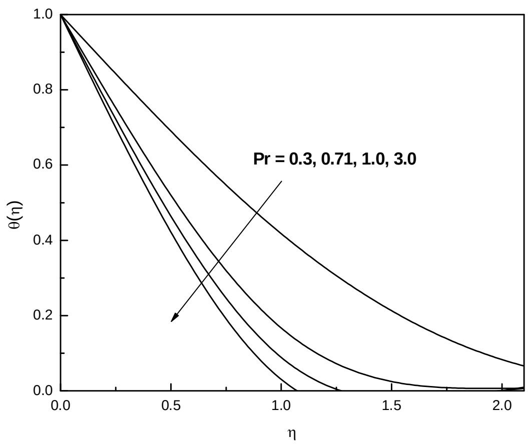

Fig. 6: Temperature Profiles for Different Values of *Pr*

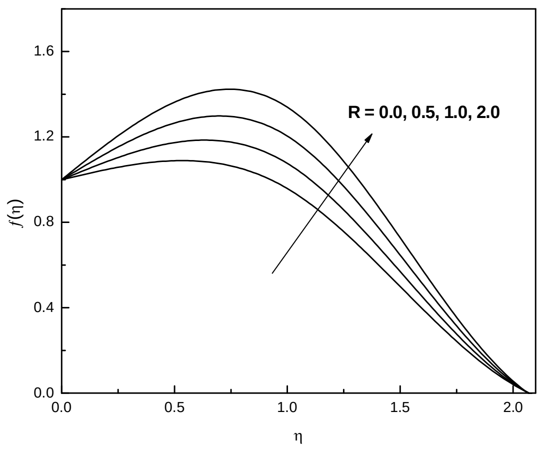

Fig. 7: Velocity Profiles for Different Values of *R*

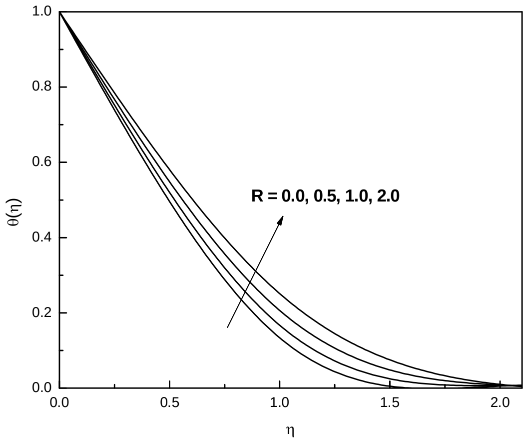

Fig. 8: Temperature Profiles for Different Values of *R*

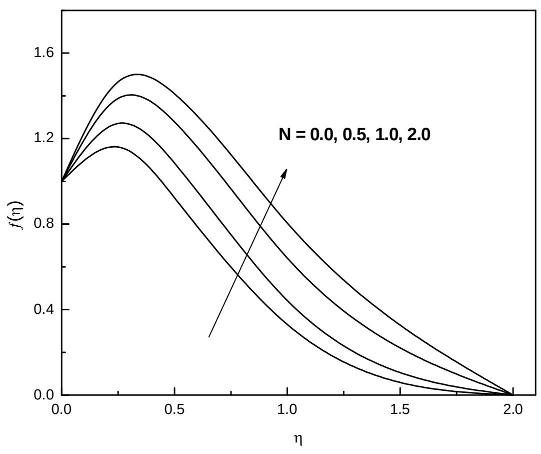

Fig. 9: Velocity Profiles for Different Values of *N*

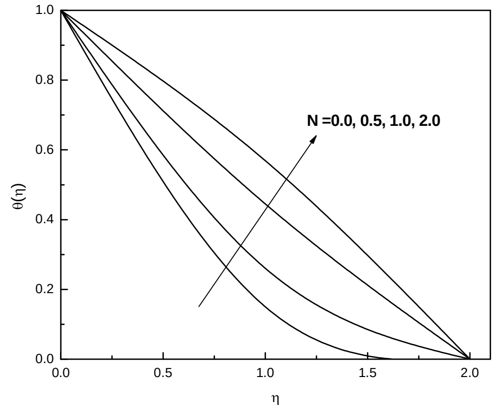

Fig. 10: Temperature Profiles for Different Values of *N*

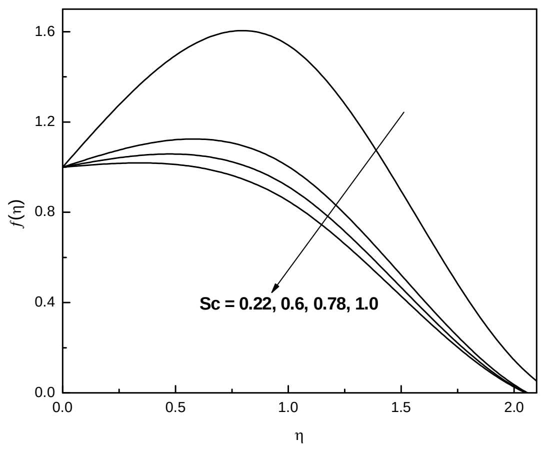

Fig.11: Velocity Profiles for Different Values of *Sc*

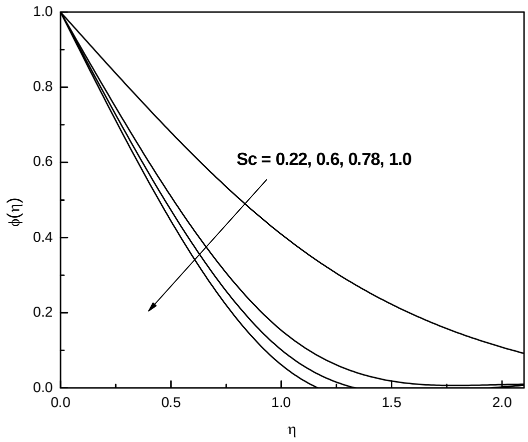

Fig.12: Concentration Profiles for Different Values of Sc

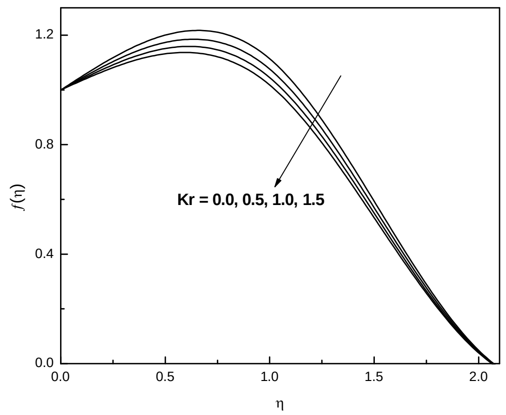

Fig. 13: Velocity Profiles for Different Values of *Kr*

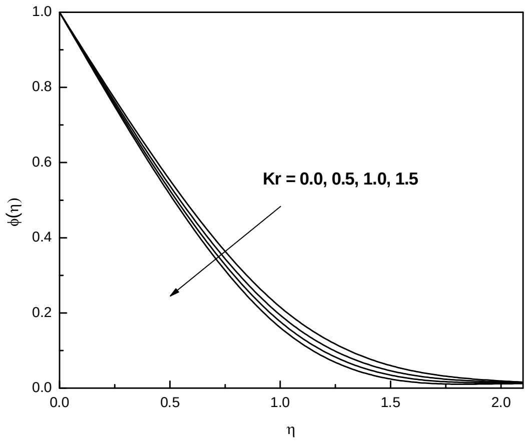

Fig. 14: Concentration Profiles for Different Values of *Kr*

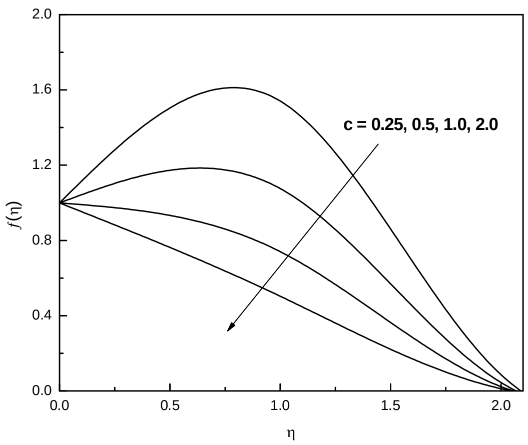

Fig. 15: Velocity Profiles for Different Values of *c*

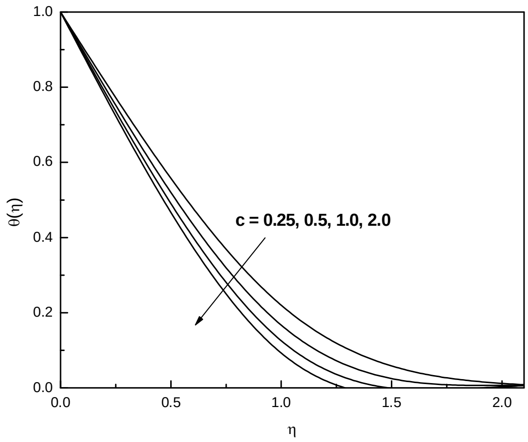

Fig. 16: Temperature Profiles for Different Values of *c*

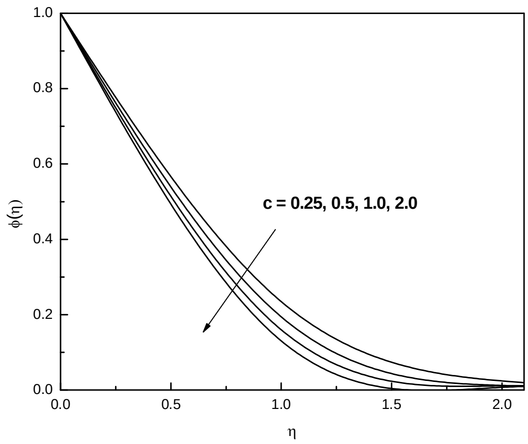

Fig. 17: Concentration Profiles for Different Values of *c*

In order to assess the accuracy of the numerical results as the results for the reduced skin-friction coefficient (C_f), Nusselt number (*Nu*) and Sherwood number (*Sh*) for different values of suction parameter (*c*) the present results compared with Makinde [14]. Comparison with the existing results shows good agreement, as presented in Table 1.

The effects of various governing parameters on the skin-friction coefficient C_f, Nusselt number *Nu* and the Sherwood number *Sh* are shown in Tables 2, 3 and 4. From Table 2, it is noticed that as Grashof number *Gr* or solutal Grashof number *Gc or* Permeability of porous parameter *K* *increases*, the skin-friction coefficient increases. It is obvious that an increase in magnetic field parameter *M* reduces the skin-friction. From Table 2, it is observed that as the Prandtl number *Pr* increases the skin-friction decreases while the Nusselt number increases. Also, it is found that an increase in the radiation parameter *R or* temperature difference parameter *N* results in an increase in the skin-friction and a decrease in the Nusselt number. From Table 3, it is seen that, as the Schmidt number *Sc* or chemical reaction parameter *Kr* increases, the skin-friction decreases while the Sherwood number increases.

6. CONCLUSIONS

In this paper the thermal radiation effects on unsteady MHD free convection flow through a moving vertical porous plate embedded in a porous medium is 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 shooting technique. The effects of various governing parameters on the skin friction, Nusselt number, and Sherwood number are shown in tables. It was found that the skin-friction coefficient increase as buoyancy parameters or porous medium increases, while it decreases as magnetic field parameter increase. It is seen that, as the Schmidt number *Sc* or chemical reaction parameter *Kr* increases, the skin-friction decreases while the Sherwood number increases. Magnetic field has significant effect on 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.

Table 1. Comparison of results of the skin-friction coefficient (C_f), Nusselt number (*Nu*) and Sherwood number (*Sh*) with previously published data for the values of $Gr = 5.0, Gc = 5.0, Sc = 0.5, Pr = 0.71, N = 0.1, R = 0.1, M = K = Kr = 0.0$.

	Makinde Results[14]	*Present Results*	*Makinde Results[14]*	*Present Results*	*Makinde Results[14]*	*Present Results*
c	C_f		*Nu*		*Sh*	
0.15	3.3082	3.308257	1.11600	1.116004	0.8957	0.895762
0.25	3.0904	3.090452	1.2126	1.212624	0.9635	0.963551
0.35	2.8608	2.860821	1.3123	1.312356	1.0332	1.033235
0.45	2.6213	2.621374	1.4149	1.414975	1.1047	1.104702
0.50	2.4985	2.498555	1.4673	1.467329	1.14107	1.141072
0.75	1.8613	1.861354	1.7382	1.738286	1.3287	1.328771
1.00	1.2002	1.200294	2.0226	2.022676	1.5251	1.525130
1.25	0.5299	0.529974	2.3180	2.318086	1.7288	1.728812

Table 2. Numerical Values of the Skin-Friction Coefficient C_f, Nusselt Number *Nu* and Sherwood number *Sh* for $Pr = 0.71, R = 0.5, N = 0.1, Sc = 0.6, Kr = 0.5, c = 0.5$.

Gr	*Gc*	*M*	*K*	C_f	*Nu*	*Sh*
10	6.0	1.0	0.5	2.12655	0.936417	1.42539
5.0	6.0	1.0	0.5	0.523755	0.936417	1.42539
7.0	6.0	1.0	0.5	1.16487	0.936417	1.42539
10	2.0	1.0	0.5	0.943549	0.936417	1.42539
10	4.0	1.0	0.5	1.53505	0.936417	1.42539
10	6.0	0.5	0.5	2.65168	0.936417	1.42539
10	6.0	0.7	0.5	2.43244	0.936417	1.42539
10	6.0	1.0	0.1	1.01146	0.936417	1.42539
10	6.0	1.0	0.3	1.66775	0.936417	1.42539

Table 3. Numerical Values of the Skin-Friction Coefficient C_f, Nusselt Number *Nu* and Sherwood number *Sh* for *Gr = 10, Gc = 6.0, K = 0.5, M = 1.0, Sc = 0.6, Kr = 0.5, c* = 0.5.

Pr	*R*	*N*	C_f	*Nu*	*Sh*
0.71	0.5	0.1	2.12655	0.936417	1.42539
1.0	0.5	0.1	1.76483	1.17492	1.42539
1.5	0.5	0.1	1.32811	1.56199	1.42539
0.71	0.1	0.1	1.88223	1.30102	1.42539
0.71	0.3	0.1	2.01002	1.08461	1.42539
0.71	0.5	0.3	2.3317	0.785535	1.42539
0.71	0.5	0.5	2.56924	0.660671	1.42539

Table 4. Numerical Values of the Skin-Friction Coefficient C_f, Nusselt Number *Nu* and Sherwood number *Sh* for *Gr = 10, Gc = 6.0, K = 0.5, M = 1.0, Pr = 0.71, R = 0.5, N = 0.1.*

Sc	*Kr*	*C*	C_f	*Nu*	*Sh*
0.6	0.5	0.5	2.12655	0.936417	1.42539
0.22	0.5	0.5	2.57732	0.936417	0.841055
0.5	0.5	0.5	2.22575	0.936417	1.27558
0.6	0.7	0.5	2.10522	0.936417	1.47207
0.6	1.0	0.5	2.07498	0.936417	1.53965
0.6	0.5	0.7	1.76879	1.06131	1.598
0.6	0.5	1.0	1.16747	1.2594	1.87126

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