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Radiation Absorption and Chemical Reaction Effects on Magnetohydrodynamic (MHD) Flow of Jeffery Fluid in an Infinite Vertical Plate

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ABSTRACT

The influence of radiation absorption and chemical reaction on unsteady MHD convective Jeffery flow of a viscous, electrically conducting and incompressible fluid is analysed. The governing equations that describe the flow formation, heat and mass transfer are modeled as Partial Differential Equations (PDEs) and solved numerically using Finite Difference Method (FDM). The effect of parameters associated with the flow of the fluid velocity, temperature and concentration were studied with the aid of graphs. It is seen that, the momentum boundary layer increases as the value of radiation and Jeffery parameters are increased while the velocity of the fluid falls for higher values of the chemical reaction parameter. Also, the temperature of the fluid rises as radiation becomes significant in the thermal boundary layer while increase in chemical reaction parameter causes a decrease is the concentration of the fluid.

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INTRODUCTION

Now a days, Magnetohydrodynamic (MHD) has been extended into wide areas of basic and applied research in sciences and engineering. The study of non-Newtonian fluid becomes very interested due to variety of technological applications like making of plastic sheets, lubricant's performance and motion of biological fluid (Ramzan *et al.,*2022). Electrically conducting fluid in presence of magnetic field and the effect of heat generation on free convection flow with heat conduction problems have received much attention by many researchers. Model studies of the free convection flows have earned reputations because of their applications in nuclear engineering problem Safiqul (Islam *et al.*, 2014).

Furthermore, free convection arises in the fluid changes when temperature changes cause density variation leading to buoyancy forces acting on the fluid elements. In recent years, the problem of free convective heat and mass transfer flows through a porous medium under the influence of magnetic field have attracted attention of of a number of researchers because of their possible applications in many branches of science and technology such as: applications in cooling re-entry vehicles and rocket boosters, cross-hatching on ablative surfaces and film vaporization in combustion chambers (Reddy *et al.*, 2016).

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Gulle and Kodi (2022) undertook research on a study of the unsteady magneto-hydrodynamic mixed convection Jeffery fluid flow over an inclined permeable moving plate in the presence of thermal radiation, heat generation, radiation, aligned magnetic field, thermophoresis effect and homogeneous chemical reaction subjected to variable suction analytically. Effects of heat and mass transfer of MHD Jeffery nanofluid flow with chemical reaction, radiation and soret was investigated by (Haritha *et al.*, 2022). Raghunath *et al.* (2022) examined unsteady MHD flow of a Jeffery fluid through a porous medium in the presence of heat absorption and chemical reaction.

On the other hand, radiative convective flows are encountered in countless industrial and environmental processes, particularly in astrophysical studies and space technology. Radiative heat and mass transfer play an important role in manufacturing industries for the design of fins, steel rolling, nuclear power plants, gas turbines and various propulsion device for aircraft, combustion and furnace design, materials processing, energy utilization temperature measurements, remote sensing for astronomy and space exploration, food processing cryogenic engineering as well as numerous agricultural, health and military applications. Radiative magnetohydrodynamic (MHD) rotating fluid flow of viscous incompressible electrically conducting Jeffery fluid was researched on by (Krishna, 2021). They used Laplace transformation method to obtain analytical solutions of governing momentum and energy equations.

Non-Newtonian transport phenomena arise in many branches of process mechanical, chemical and materials engineering. Such fluids exhibit shear-stress-strain relationships which diverge significantly from the classical Newtonian (Navier Stokes) model. Among the several non-Newtonian models proposed, Jeffrey's fluid model is significant because Newtonian fluid model can be deduced from this as a special case by taking $k_1 = 0$. Further, it is speculated that the physiological fluids such as blood exhibit Newtonian and non-Newtonian behaviors during circulation in a living body. As with a number of rheological models developed, the Jeffrey's model has proved quite successful.

The nonlinear, steady state boundary layer flow, heat and mass transfer of an incompressible non-Newtonian Jeffrey's fluid past a semi-infinite vertical plate was examined by Gaffar *et al.* (2017). Noor *et al.* (2020) reported the numerical study is presented for the magnetohydrodynamic (MHD) squeezing flow of Jeffrey fluid between two parallel plates in a porous medium with the presence of thermal radiation, heat generation/absorption and chemical reaction. Heat and mass transfer plays a relevant role in manufacturing, geothermal, geophysical, technological and engineering processes. For the design of fins, steel rolling, nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles, space craft design, satellites and space vehicles. The usefulness of heat and mass transfer can also be explored in our environment in drying, filtration processes and saturation of porous materials by chemicals (Omokhuale and Jabaka, 2019). Chemical reactions usually accompany a large amount of exothermic and exothermic reactions. These characteristics can be easily seen in a lot of engineering processes. Recently, it has been realized that it is not always permissible to neglect the convection effects in porous constructed chemical reactors (Hassan and Reddy, 2018). Uwanta and Omokhuale (2014) and Uwanta *et al.* (2014) conducted research of Jeffery fluid flow numerically using FDM.

Hayat *et al.* (2017) examined the effects of chemical reaction in the two-dimensional flow of Jeffrey liquid due to nonlinear radially stretched surface. The flow analysis is conducted under the action of applied magnetic field. Heat transfer is considered in the presence of Joule heating, heat generation/absorption and Newtonian heating. Convergent solutions to the nonlinear formulation are developed. Krishna (2022) presented the numerical investigation of Newtonian heating effect on unsteady MHD free convective flow.

In this study, motivated by the above studies and applications, a novel investigation has been conducted to study unsteady convective Jeffery flow in the presence of radiation absorption and chemical reaction. The flow is governed by a modeled coupled nonlinear system of partial differential equations (PDEs) in dimensional form which are transformed into non-dimensional form using some non-dimensional variables. The numerical solutions of the resulting equations were gotten by employing FDM for the velocity, temperature and concentration of the fluid. Furthermore, the effects of physical parameters associated with the fluid flow were analysed with the help of graphs and discussed.

2.0 Mathematical Formulation

We considered an unsteady two–dimensional flow of an electrically conducting incompressible viscous fluid past an infinite vertical porous plate moving with Jeffery fluid. As the plate is infinite in extent, the physical variables are functions of y^* and t^* where y^* is taken normal to the plate and the x^*-direction is taken along the plate in the vertical upward direction, where fluid suction or injection and magnetic field are imposed at the plate surface. The temperature and concentration of the fluid are raised to T_w^* and C_w^* respectively and are higher than the ambient temperature and that of fluid. In addition, the effect of chemical and heat absorptions and radiation absorption effects is taken into account. It is assumed that induced magnetic field is negligible.

We further assumed that the Boussinesq and boundary-layer approximations hold, the basic equations which govern the problem are be given by:

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

$$\frac{\partial u^*}{\partial t^*}+v^*\frac{\partial u^*}{\partial y^*}=\frac{\nu}{1+\lambda_1}\frac{\partial^2 u^*}{\partial y^{*2}}+g\beta\left(T^*-T_\infty^*\right)+g\beta^*\left(C^*-C_\infty^*\right)-\frac{\sigma B_0^2}{\rho}u^*-\frac{\nu}{K_1}u^* \tag{2}$$

$$\frac{\partial T^*}{\partial t^*}+v^*\frac{\partial T^*}{\partial y^*}=\frac{k}{\rho Cp}\frac{\partial^2 T^*}{\partial y^{*2}}-\frac{1}{\rho Cp}\frac{\partial q_r}{\partial y'}+\frac{Q}{\rho Cp}\left(T^*-T_\infty^*\right)+Q_1\left(C^*-C_\infty^*\right) \tag{3}$$

$$\frac{\partial C^*}{\partial t^*}+v^*\frac{\partial C^*}{\partial y^*}=D\frac{\partial^2 C^*}{\partial y^{*2}}-R_1\left(C^*-C_\infty^*\right) \tag{4}$$

with the following initial and boundary conditions:

$$\left.\begin{array}{l} t^*\le 0, u^*=0, T^*\to T_\infty^*, C^*\to C_\infty^* \; for\, all\; y^* \\ t^*>0, u^*=0, \dfrac{\partial T^*}{\partial y^*}=-\dfrac{q}{k}, \dfrac{\partial C^*}{\partial y^*}=-\dfrac{q_m}{k_m} \; at\; y^*=0 \\ \quad u^*\to 0, T^*\to T_\infty^*, C'\to C_\infty^* \; as\; y^*\to\infty \end{array}\right\} \tag{5}$$

The radiative heat flux term by using Rosseland approximation is given by

$$q_r=-\frac{4\sigma^*}{3a_R}\frac{\partial T^4}{\partial y'} \tag{6}$$

where u^* and v^* are velocity components in x^* and y^* directions respectively, T is the temperature, t is the time, g is the acceleration due to gravity, β is the thermal expansion coefficient, β^* is the concentration expansion coefficient, υ is the kinematic viscosity, D is the chemical molecular diffusivity, C_p is heat capacity at constant pressure, B_0 is a constant magnetic field intensity, σ is the electrical conductivity of the fluid, q_r is the radiative heat flux, q_m is the mass heat flux per unit area at the plate, k_m is mass diffusivity, σ^* is the Stefan-Boltzmann constant, k_0 is the variable thermal conductivity, C_S is the concentration susceptibility, ρ is the density, λ_1 is the Jeffery fluid, q is the constant heat flux per unit area at the plate, T_∞^* is the free stream temperature, C_w is the species concentration at the plate surface, C_∞^* is the free stream concentration,

Q_1 is the mass absorption coefficient, Q is the heat generation coefficient. $v_0 > 0$ is the suction parameter and $v_0 < 0$ is the injection parameter. On introducing the following non-dimensional quantities

$$\left.\begin{array}{l} u=\dfrac{u'}{u_0}, y=\dfrac{y'u_0}{\nu}, \nu=\dfrac{\mu}{\rho}, t=\dfrac{t'u_0}{t_0}, \theta=\dfrac{\left(T'-T'_\infty\right)k_0u_0}{q\nu}, C=\dfrac{\left(C'-C'_\infty\right)k_mu_0}{q_m\nu} \\ \Pr=\dfrac{\mu Cp}{k_0}, M=\dfrac{\sigma B_0^2\nu}{\rho u_0{}^2}, K=\dfrac{\nu^2}{K^*u_0{}^2}, Gr=\dfrac{g\beta\nu^2q}{k_0u_0{}^4}, Gc=\dfrac{g\beta^*\nu^2q}{k_mu_0{}^4} \\ Sc=\dfrac{\nu}{D}, S=\dfrac{Q\nu}{\rho Cpu_0{}^2}, \lambda=\dfrac{Q_1\nu}{u_0{}^2}, \chi=\dfrac{R_1\nu}{u_0}, \xi=\dfrac{v_0}{u_0}, R=\dfrac{4\sigma^*T_\infty^3}{3u_0a_R} \end{array}\right\} \tag{7}$$

where u_0 and t_0 are reference velocity and time respectively.

Using (1), (6) and (7), equations (2) - (4) are transformed into the following:

$$\frac{\partial u}{\partial t}-\xi\frac{\partial u}{\partial y}=\frac{1}{1+\lambda_1}\frac{\partial^2u}{\partial y^2}+Gr\theta+GcC-Mu-Ku \tag{8}$$

$$\frac{\partial\theta}{\partial t}-\xi\frac{\partial\theta}{\partial y}=\frac{1}{\Pr}\left(1+R\right)\frac{\partial^2\theta}{\partial y^2}+S\theta+\lambda C \tag{9}$$

$$\frac{\partial C}{\partial t}-\xi\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2C}{\partial y^2}-\chi C \tag{10}$$

The corresponding boundary conditions are:

$$\left.\begin{array}{l} t\le 0, u=0, \theta=0, C=0 \ for\, all\ y \\ t>0, u=0, \dfrac{\partial\theta}{\partial y}=-1, \dfrac{\partial C}{\partial y}=-1 \ at\ y=0 \\ u\to 0, \theta\to 0, C\to 0\, as\ y\to\infty \end{array}\right\} \tag{11}$$

where Gr is the thermal Grashof number, Gc is the mass Grashof number, Sc is the Schmidt number, $\Pr$ is the Prandtl number, M is the magnetic parameter, K is the permeability parameter, ξ is the suction parameter, χ is chemical reaction parameter, R is radiation, S is the heat generation parameter.

Equations (3.22) to (3.25) are now approximated by implicit finite difference schemes of Crank – Nicolson type. The finite difference approximations of these equations are as follows:

$$\left(\frac{u_{i,j+1}-u_{i,j}}{\Delta t}-\gamma\frac{u_{i+1,j}-u_{i,j}}{\Delta y}\right)=\frac{1}{(1+\lambda_1)}\left[\frac{u_{i+1,j}+u_{i-1,j}-2u_{i,j}+u_{i+1,j+1}+u_{i-1,j+1}-2u_{i,j+1}}{2(\Delta y)^2}\right]$$

$$+\frac{Gr}{2}\left(\theta_{i,j+1}+\theta_{i,j}\right)+\frac{Gc}{2}\left(C_{i,j+1}+C_{i,j}\right)-\frac{M}{2}\left(u_{i,j+1}+u_{i,j}\right)-\frac{K}{2}\left(u_{i,j+1}+u_{i,j}\right) \quad (12)$$

$$\left(\frac{\theta_{i,j+1}-\theta_{i,j}}{\Delta t}-\gamma\frac{\theta_{i+1,j}-\theta_{i,j}}{\Delta y}\right)=\frac{1}{\Pr}\cdot[1+R]\left[\frac{\theta_{i+1,j}-\theta_{i-1,j}-2\theta_{i,j}+\theta_{i+1,j+1}+\theta_{i-1,j+1}-2\theta_{i,j+1}}{2(\Delta y)^2}\right]$$

$$+\frac{S}{2}\left(\theta_{i,j+1}+\theta_{i,j}\right)+\frac{\lambda}{2}\left(C_{i,j+1}+C_{i,j}\right) \quad (13)$$

$$\left(\frac{C_{i,j+1}-C_{i,j}}{\Delta t}-\gamma\frac{C_{i+1,j}-C_{i,j}}{\Delta y}\right)=\frac{1}{Sc}\left[\frac{C_{i+1,j}-C_{i-1,j}-2C_{i,j}+C_{i+1,j+1}+C_{i-1,j+1}-2C_{i,j+1}}{2(\Delta y)^2}\right]$$

$$-\frac{\chi}{2}\left(C_{i,j+1}+C_{i,j}\right) \quad (14)$$

The initial and boundary conditions become

$$\begin{aligned} &u_{i,0}=0,\theta=0,C_{i,0}=0 \text{ for all i except } i=0\\ &u_{i,0}=0,\frac{\theta_{i+1,j}-\theta_{i,j}}{\Delta y}=-1,\frac{C_{i+1,j}-C_{i,j}}{\Delta y}=-1\\ &u_{l,0}=0,\theta_{l,0}=0,C_{l,0}=0 \end{aligned} \quad (15)$$

where l corresponds to ∞. The suffix i corresponds to y and j is equals to t. consequently,

$\Delta t=t_{j+1}-t_j$ and $\Delta y=y_{i+1}-y_i$.

In order to access the effects of parameters on the flow variables namely; Jeffery parameter, thermal Grashof number, mass Grashof number, Schmidt number, Prandtl number, magnetic parameter, chemical absorption, Dufour number, permeability parameter, suction parameter, heat generation parameter, radiation parameter, chemical reaction parameter and Eckert number on the velocity, temperature and concentration, and have grips of the physical problem, the unsteady coupled non-linear partial differential equations (12) – (14) with boundary conditions (15) have been solved using Maple package with the following values for Gr = Gc = M = η = 1, $\lambda_1=0.5$, *Pr* = 0.71, *Sc* = 0.3, S = 0.1, χ = 0.5, R = 0.1, K= 0.5, $\xi=0.5$ except where they are varied. A step size of $\Delta t=0.01$, Δy = 0.25 is used for the interval $y_{\min}$ = 0 to $y_{\max}$ = 1 for a desired accuracy and a convergence criterion of 10^{-6} is satisfied for various parameters.

4.2 Results and Discussion

For the values of C, θ, u at time t, the values at a time $t+\Delta t$ gotten for $i=1,2,...,l-1$ in (14) which results in a tri-diagonal system of equations in unknown values of C. Similarly, calculating θ and u from (13) and (12) respectively. If $\lambda_1 = M = K = Gc = S = 0,$

$Sc = \lambda = R = \chi = 0$, and Gr = 1, the results of Soundalgekar *et al.* (2004) are gotten.

Also, at $\frac{\partial u}{\partial t} = \frac{\partial \theta}{\partial t} = m = K = Gc = S = \lambda = R = N = 0$, and $Gr = -1,$

$\xi = -1$, the results of Aruna Kumari *et al.* (2012) are obtained.

4.2.1 Velocity profiles

Figures 1 to 6 represent the velocity profiles with varying parameters respectively. Figure 1 depicts the effect of thermal Grashof number on the velocity. It is observed that, the velocity increases with increasing thermal Grashof number. Influence of mass Grashof number on the velocity is presented in Figure 2, It is found that, the velocity rises with the increase in mass Grashof number. Figure 3 shows variation of Magnetic parameter on the velocity profile. It is noted that, the velocity decreases with increase in Magnetic parameter. It is now well documented that the magnetic field dampens the velocity by generating drag force that opposes the motion of the fluid, resulting in a decrease in velocity. The magnetic field resists transport phenomena. This is because a change in M causes a change in the Lorentz force owing to the magnetic field, and the Lorentz force generates more resistance to transport events. Influence of radiation on the velocity profile is depicted in Figure 4, It is observed that, the velocity increases with increasing radiation parameter. Figure 5 illustrates different values of chemical reaction on the velocity. It is found that, the velocity decreases with the increase of the chemical reaction parameter. Influence of Jeffery parameter on the velocity is presented in Figure 6. It is clear that, the velocity increases with increase in Jeffery parameter.

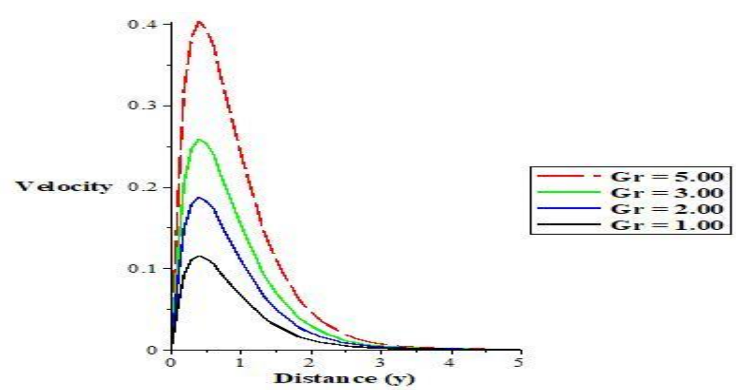

Figure 1: Velocity profiles for different values of Gr.

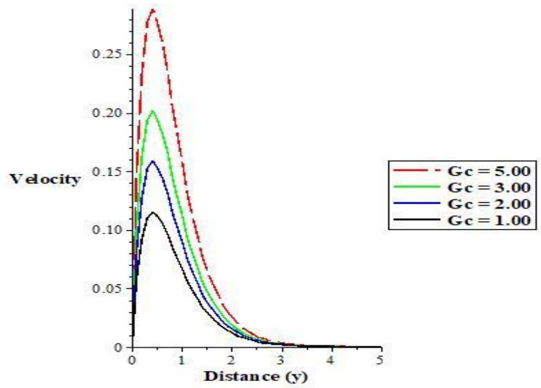

Figure 2: Velocity profiles for different values of Gc.

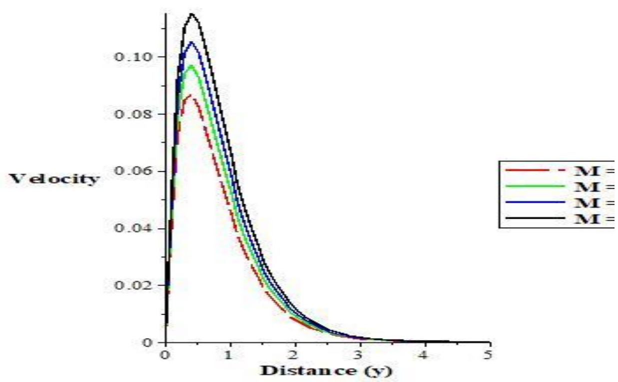

Figure 3: Velocity profiles for different values of M.

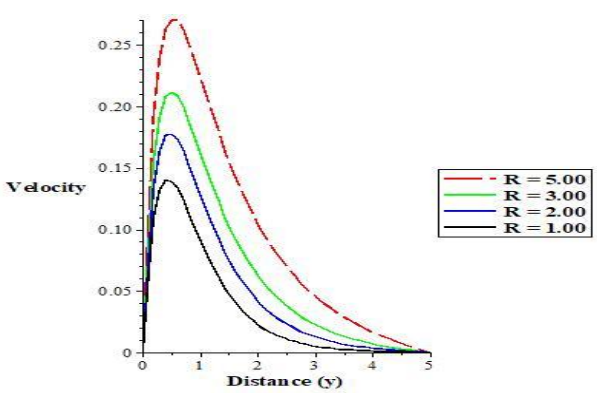

Figure 4: Velocity profiles for different values of R .

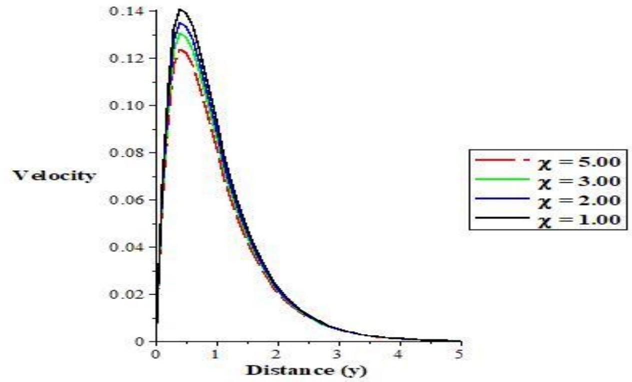

Figure 5: Velocity profiles for different values of χ .

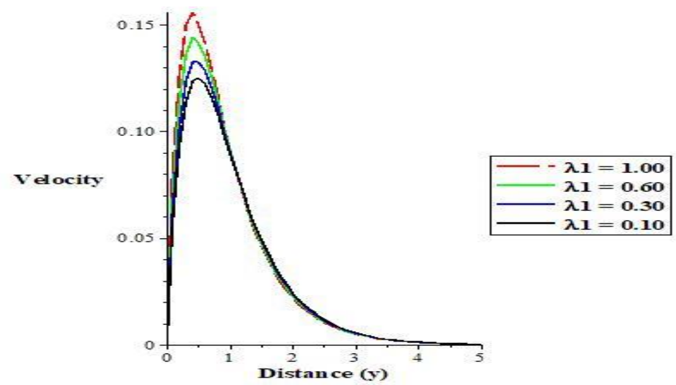

Figure 6: Velocity profiles for different values of λ_1 .

4.2.2 Temperature profiles

Figures 7 and 8 illustrate the temperature profiles. In Figure 7, the influence of Prandtl number on the temperature is demonstrated. It is seen that, the temperature decreases when the Prandtl number is increased. Since the smaller Prandtl value is the equivalent to an increase in the heat conductivity of the fluid, heat can be distributed more quickly from the heated surface for higher Prandtl values. Figure 8 represents influence of radiation on the temperature. It is depicted that, the temperature increases with increase in radiation.

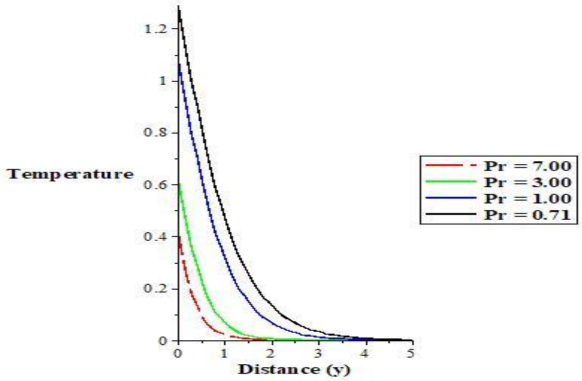

Figure 7: Temperature profiles for different values of Pr.

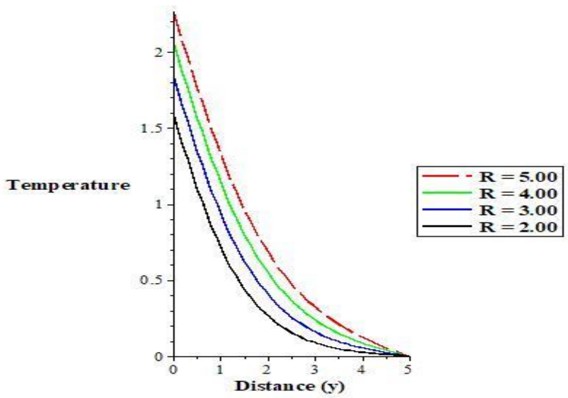

Figure 8: Temperature profiles for different values of R.

4.2.3 Concentration profiles

Figures 9 to 10 show the concentration profiles. Influence of Schmidt number on the concentration is presented in Figure 9. It is noted that, the concentration is lower due to increasing Schmidt number. Physically the Schmidt number is the momentum to mass diffusivities ratio. For enhancement of the Schmidt number the mass diffusivity diminishes, which is responsible for the reduction of the concentration. In Figure 10, the influence of chemical reaction parameter on the concentration is shown. It is demonstrated that. The concentration is lower as the chemical reaction parameter is increased.

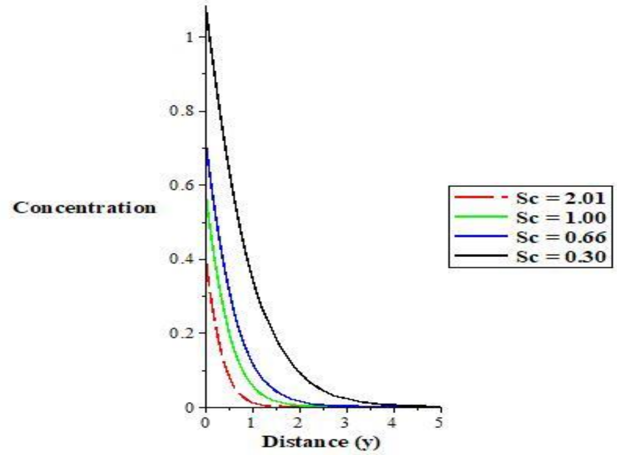

Figure 9: Concentration profiles for different values of Sc.

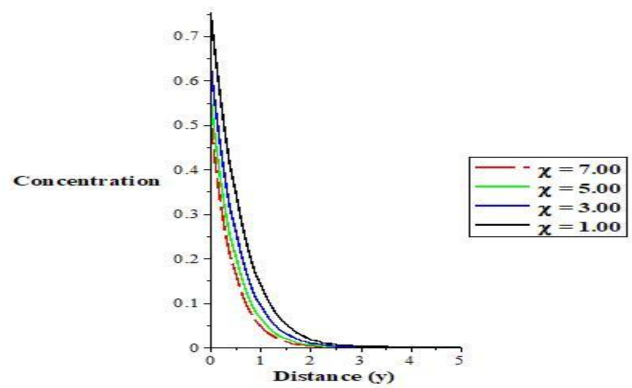

Figure 10: Concentration profiles for different values of χ

The effects of various governing parameters on skin-friction coefficient C_f, Nusselt number Nu and Sherwood number Sh are displayed in Table 4.1. In order to emphasis the contributions of each parameter, one parameter is varied while the rest take default fixed values.

From Table 4.1, it is observed that increase in S, λ_1 and R causes rise in the skin-friction coefficient, Nusselt number and Sherwood number respectively, while an increase in $\Pr$ reduces the skin-friction coefficient, Nusselt number and Sherwood number respectively. It is also seen that as Sc increases there is a fall in the skin-friction coefficient and a rise in Nusselt and Sherwood numbers respectively.

Table 4.1 Skin-friction coefficient C_f, Nusselt number Nu and Sherwood number Sh for various physical parameters ($\Pr, \chi, S, Sc$) with fixed values of

($Gr = 1.0, Gc = 1.0, M = 1.0, \lambda = 0.5, k = 0.5, t = 0.2$)

$\Pr$	S	λ_1	R	Sc	C_f	Nu	Sh
0.71	1.0	1.0	0.2	0.22	0.4148	3.0257	1.4333
3.0	1.0	1.0	0.2	0.22	0.2988	0.6168	1.4287
0.71	1.0	1.0	0.2	0.22	0.4151	3.0311	1.4343
0.71	**3.0**	1.0	0.2	0.22	0.4163	3.0729	1.4724
0.71	1.0	**2.0**	0.2	0.22	0.4129	3.0523	1.5721
0.71	1.0	1.0	**2.0**	0.22	0.4243	3.2477	1.6427
0.71	1.0	1.0	0.2	**2.01**	0.3629	3.0983	1.7256

CONCLUSION

We studied unsteady MHD convective Jeffery flow with radiation absorption and chemical reaction effects. The problem is modeled by a system coupled non-linear PDEs and solved by FDM. Computations were carried out to examine the effects of physical parameters on the fluid velocity, temperature and concentration. The following conclusion can be deduced from this study:

1. The fluid concentration reduces due to higher values of chemical reaction and Schmidt number.
2. Higher values of radiation parameter led to increase thermal boundary layer of the fluid while an opposite trend is found as the Prandtl number is increased.
3. The momentum boundary layer rises as the values of radiation parameter, thermal and mass Grashof numbers and Jeffery parameter are increased while the velocity of the fluid falls as chemical reaction and magnetic field parameters become significant.
4. When the numerical results of this study are compared with results in literatures a good agreement was observed.

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