Radiation Absorption and Dufour Effects on MHD Flow in Vertical Surface with Chemical Reaction

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Abstract

This study analytically explores the combined effects of chemical reactions, thermal diffusion, and radiation absorption on magnetohydrodynamic (MHD) flow along a vertical surface. The governing equations, incorporating relevant physical parameters, are solved using a perturbation technique. The impact of various dimensionless parameters on velocity, temperature, and concentration profiles is thoroughly analyzed and discussed.

Keywords: MHD, chemical reaction, radiation absorption, Dufour effect, thermal diffusion.

1. INTRODUCTION

Heat and mass transfer in fluid flow across vertical and horizontal surfaces have critical applications in various industrial and environmental processes. These include polymer extrusion, food drying, cooling towers, and ceramic fabrication. The interactions among thermal radiation, magnetic fields, and chemically reactive species introduce complex behaviours worth detailed investigation.

In view of the above, the effects of heat and mass transfer for MHD flow in vertical surface with radiation absorption studied by Kesavaiah and Sudhakaraiah [1]. Kesavaiah et. al [2] investigated the effects of the chemical reaction and radiation absorption on an unsteady MHD flow in vertical permeable moving plate embedded in a porous medium with heat source and suction. Convective heat and mass transfer flow from a vertical surface with radiation, chemical reaction and heat source/absorption investigated by Karunakar Reddy et.al [3]. Radiation and thermo - diffusion effects on mixed convective heat and mass transfer flow of a viscous dissipated fluid over a vertical surface in the presence of chemical reaction with heat source have been studied by Kesavaiah et. al [4].

Radiation and mass transfer effects on MHD mixed convection flow from a vertical surface with Ohmic heating in the presence of chemical reaction studied by Kesavaiah et.al [5]. Kesavaiah and Satyanarayana [6] investigated radiation absorption and Dufour effects to MHD flow in vertical surface. Lavanya and Kesavaiah [7] have studied radiation and soret effects to MHD flow in vertical surface with chemical reaction and heat generation through a porous medium.

Chamkha [8] investigated unsteady convective heat and mass transfer past a semi-infinite porous moving plate with heat absorption. Shanker et al. [9] studied a numerical solution for radiation and mass transfer effects on unsteady MHD free convective fluid flow embedded in a porous medium with heat generation/absorption using Galerkin finite element method. Hady et al. [10] investigated the problem of free convection flow along a vertical wavy surface embedded in electrically conducting fluid saturated porous media in the presence of internal heat generation or absorption effect. Hossian et al. [11] investigated the problem of natural convection flow along a vertical wavy surface in the presence of heat generation/absorption with uniform surface temperature boundary condition. Balamurugan et a [12] investigated the effects of chemical reaction, thermal radiation and radiation absorption on unsteady double diffusive free convection flow of Kuvshinski fluid under the influence of a uniform transverse magnetic field over past a moving porous plate with heat generation.

Motivated by these foundational works, the present paper focuses on MHD flow past a moving vertical plate incorporating chemical reactions, radiation absorption, and thermal diffusion (Dufour effect). The fluid motion is steady, laminar, and incompressible, with negligible induced magnetic fields and viscous dissipation. Governing equations are solved analytically via perturbation expansion to characterize the influence of key parameters on flow characteristics.

2. FORMULATION OF THE PROBLEM

Consider a two-dimensional, steady, laminar flow of a viscous, incompressible fluid along a vertical plate moving upwards with uniform velocity. The system is subject to a transverse magnetic field and heat generation effects. The coordinate system is defined such that the x-axis lies along the plate and the y-axis is normal to it.

Assumptions:

- Constant fluid properties except for density variations in buoyancy terms (Boussinesq approximation).
- Negligible induced magnetic field and viscous dissipation.
- Constant wall temperature and species concentration.

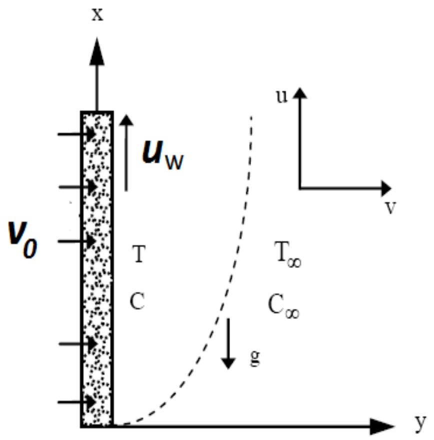

Figure: Flow configuration and coordinate system

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=g\beta\left(T'-T'_\infty\right)+g\beta^*\left(C'-C'_\infty\right)+\nu\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2}{\rho}-\frac{\nu}{K_p}u \tag{2}$$

Energy equation

$$\rho C_p\left(u\frac{\partial T'}{\partial x}+v\frac{\partial T'}{\partial y}\right)=k\frac{\partial^2 T'}{\partial y^2}+Q_l'\left(C'-C'_\infty\right)+\frac{D_M K_T}{C_s C_p}\frac{\partial^2 C'}{\partial y^2} \tag{3}$$

Diffusion equation

$$u\frac{\partial C'}{\partial x}+v\frac{\partial C'}{\partial y}=D\frac{\partial^2 C'}{\partial y^2}-Kr'\left(C'-C'_\infty\right) \tag{4}$$

The initial and boundary conditions

$$u = u_w, v = -v_0 \; const, < 0, \frac{\partial T}{\partial y} = -\frac{q}{k}, \frac{\partial C}{\partial y} = -\frac{j''}{k} \quad at \quad y = 0$$
$$u \to 0, T \to T'_\infty, C \to C'_\infty \qquad as \quad y \to \infty \tag{5}$$

Where u, are velocity components in x and y directions respectively. g is the acceleration due to gravity, β is volumetric coefficient of thermal expansion, β^* is the volumetric coefficient of expansion with concentration, is the temperature of the fluid, C' is the species concentration, T'_w is the wall temperature, C'_w is the concentration at the plate, T'_∞ is the free steam temperature far away from the plate, C'_∞ is the free steam concentration in fluid far away from the plate, ν is the kinematic viscosity, D is the species diffusion coefficient, Kr is the chemical reaction parameter. The term is assumed to be the amount of heat generated or absorbed per unit volume. Q_0 is a constant, which may take on either positive or negative values. When the wall temperature T'_w exceeds the free steam temperature T'_∞, the source term represents the heat source $Q_0 > 0$ when and heat sink when $Q_0 < 0$. The first term and second term on the right hand side of the momentum equation (2) denote the thermal and concentration buoyancy effects respectively.

The governing equations are non-dimensionalizing by using the following non-dimensional variables

$$Y = \frac{y v_o}{\nu},\ U = \frac{u}{u_w},,\ \Pr = \frac{\mu C_p}{k},\ Q = \frac{Q_0 \nu}{\rho C_p v_0^2}, Sc = \frac{\nu}{D}, k = \frac{K_p v_0^2}{\nu^2}$$
$$Gr = \frac{\nu g \beta \left(\frac{q\nu}{k v_0}\right)}{u_w v_0^2},\ Gc = \frac{\nu g \beta^* \left(\frac{j''\nu}{k v_0}\right)}{u_w v_0^2}, T = \frac{T' - T'_\infty}{\left(\frac{q\nu}{k v_0}\right)}, C = \frac{C' - C'_\infty}{\left(\frac{j''\nu}{k v_0}\right)} \tag{6}$$
$$Ql = \frac{Ql' j'' \nu}{q v_0^2 \rho C_p}, R = \frac{4 q \nu I}{k v_0}, Kr = \frac{Kr' \nu}{v_0^2}, M = \frac{\sigma B_0^2 \nu}{\rho}$$

After non-dimensionalizing the governing equations{using Eq.(6)}, the non-dimensional form of Eqs. (2) to (4) become,

$$\frac{d^2U}{dY^2} + \frac{dU}{dY} - \left(M + \frac{1}{k}\right)U = -GrT - GrC \tag{7}$$

$$\frac{d^2T}{dY^2}+\Pr\frac{dT}{dY}=-Q_l\Pr C-Du\Pr\frac{d^2C}{dY^2} \tag{8}$$

$$\frac{d^2C}{dY^2}+Sc\frac{dC}{dY}-KrSc\,C=0 \tag{9}$$

The corresponding initial and boundary conditions in non-dimensional form are

$$\begin{aligned}&U=1,\frac{\partial T}{\partial Y}=-1,\frac{\partial C}{\partial Y}=-1 \quad at \quad Y=0\\&U\to 0,T\to 0,C\to 0 \quad as \quad Y\to\infty\end{aligned} \tag{10}$$

The radiative heat flux q_r is given by equation (5) in the spirit of Cogly et.al [6]

$$\frac{\partial q_r}{\partial y}=4\left(T-T_\infty\right)I \tag{11}$$

where $I=\int_0^\infty K_{\lambda w}\frac{\partial e_{b\lambda}}{\partial T}d\lambda,\ K_{\lambda w}-$ is the absorption coefficient at the wall and $e_{b\lambda}-$ is Planck's function, I is absorption coefficient

Where Gr is the thermal Grashof number, Gc is the solutal Grashof number, $\Pr$ is the fluid Prandtl number, Sc is the Schmidt number and Kr is the chemical reaction parameter, Q is the heat generation/absorption parameter and Q_l is the radiation absorption parameter.

3. METHOD OF SOLUTION

The non-dimensional governing Eqs. (7), (8) and (9) have been solved analytically with the initial and boundary conditions given in Eq.(10). Then we get velocity, temperature and concentration as follows

$$U=\left(A_1+A_3\right)e^{m_2y}+A_2e^{m_4y}+A_4e^{m_6y} \tag{12}$$

$$T=\left(J_1+J_2\right)e^{m_2y}+J_3e^{m_4y} \tag{13}$$

$$C=-\frac{1}{m_2}e^{m_2y} \tag{14}$$

4. RESULTS AND DISCUSSION

The effect of Schmidt number on velocity is presented in Fig.1 . This shows that velocity decreases as the Schmidt number increases. Physically this is true because of the increase in Schmidt number the viscosity of the fluid increases and hence velocity decreases.

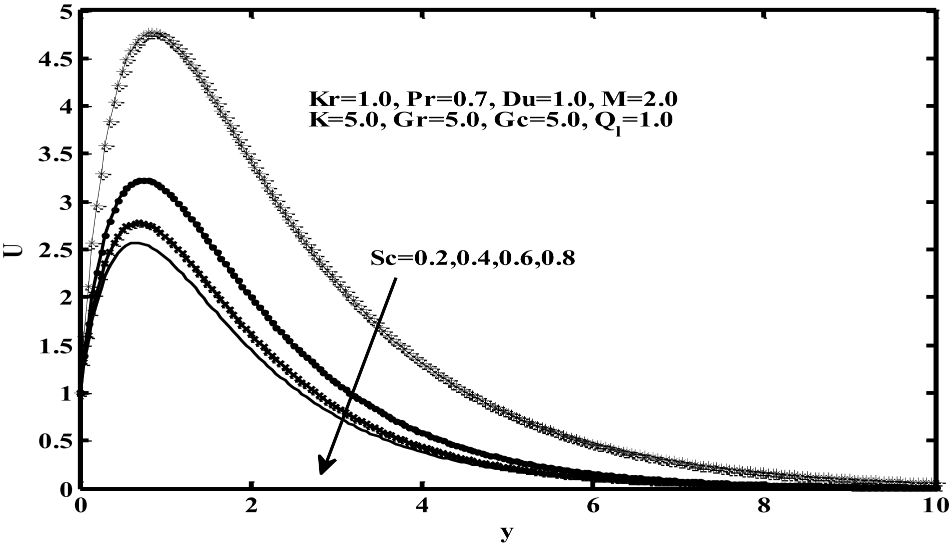

Figure (1); Velocity Profiles for different values of Sc

From Fig.2, the effect is noticed in the presence of chemical reaction parameter. It is quite interesting to observe that the same reaction observed in Fig.3 for Prandtl number. It is know that lower thermal conductivity material has high velocity and higher thermal conductivity material have lower velocity.

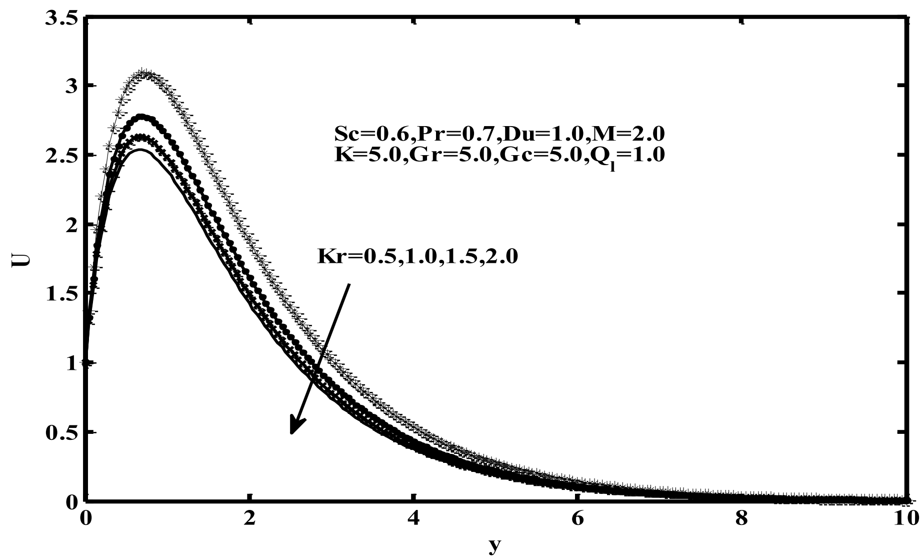

Figure (2): Velocity Profiles for different values of Kr

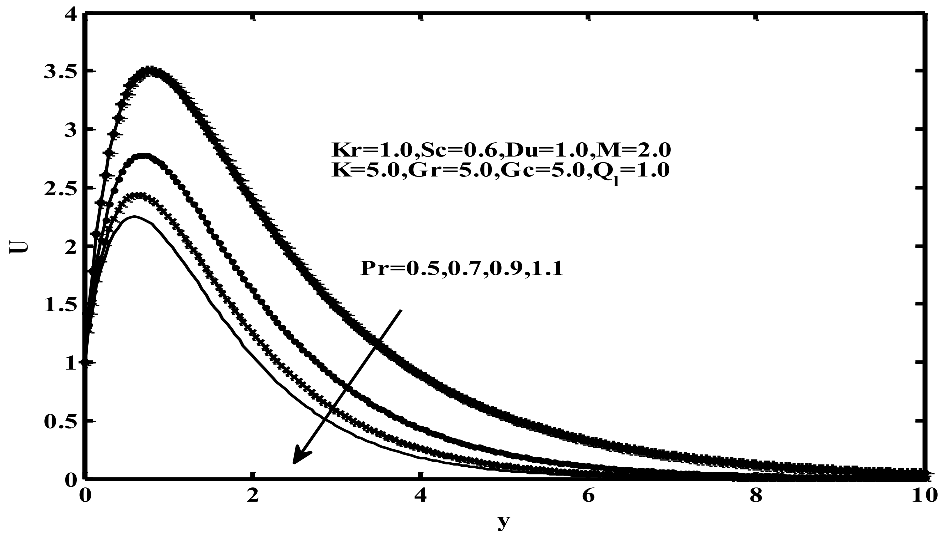

Figure (3): velcoity Profiles for different values of Pr

Fig. 4 shows the velocity profiles for different Dufour parameter, it observed that the velocity increases with increasing values of Dufour parameter. The Effect of magnetic parameter on the velocity distribution is shown in Fig. 5. From this figure it is noticed that as the magnetic parameter increases the velocity is decreases. This is due to the fact that the application of transverse magnetic field, that acts as a drag force, which is termed as Lorentz force. This force has the normal tendency of decreasing the velocity. This influence of this force is very significant near the surface compared to for away from the surface, where velocity is in stationary condition. Physically, increase in the permeability of porous medium tends to clear fluid surface.

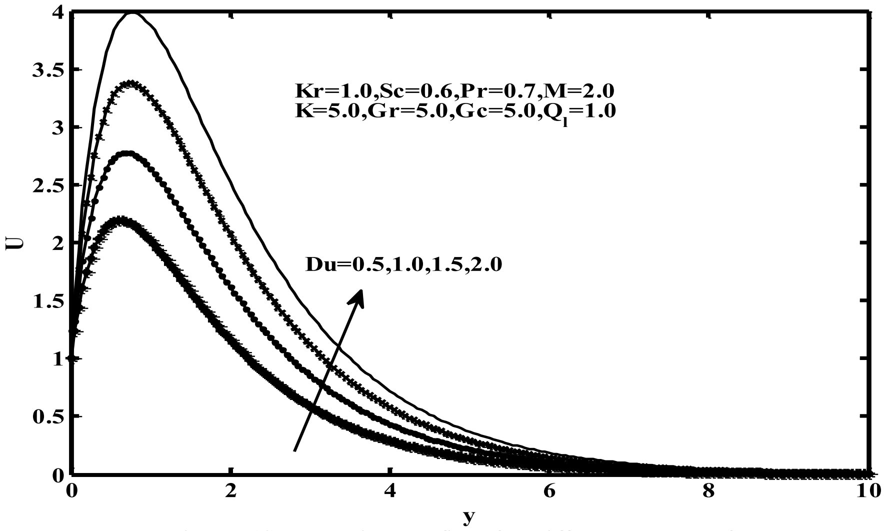

Figure (4); Velocity Profiles for different values of Du

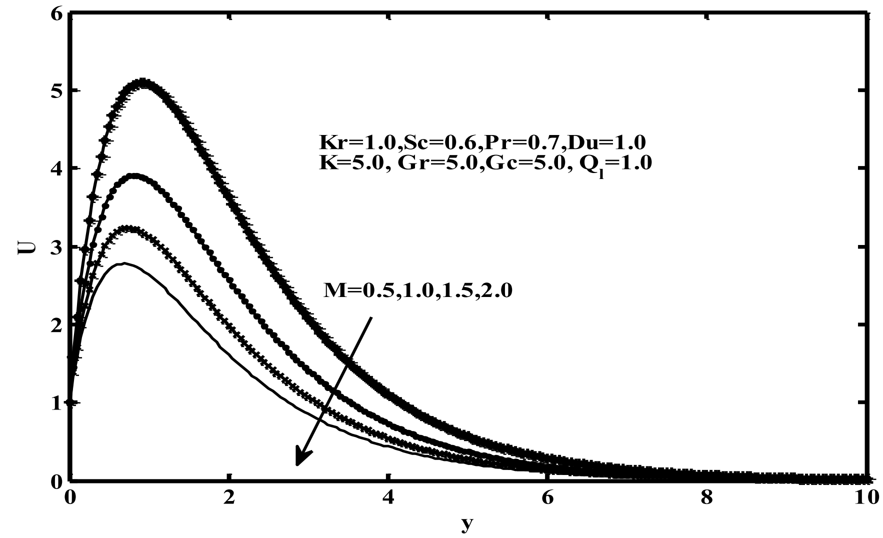

Figure (5); Velocity Profiles for different values of M

From Fig. 6, the effect of porosity parameter is shown. This figure be to contemporaneous that an increase in porosity parameter increase the velocity. From Fig. 7 and Fig. 8, the effects of Grashof number and modified Grashof number are shown. From these figures it is evident that velocity increases with the increasing values of these two parameters.

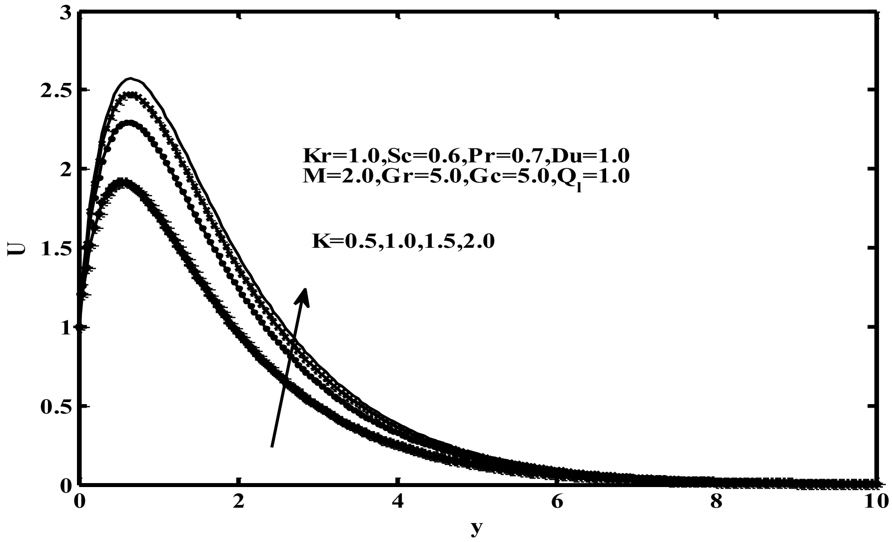

Figure (6): velcoity Profiles for different values of K

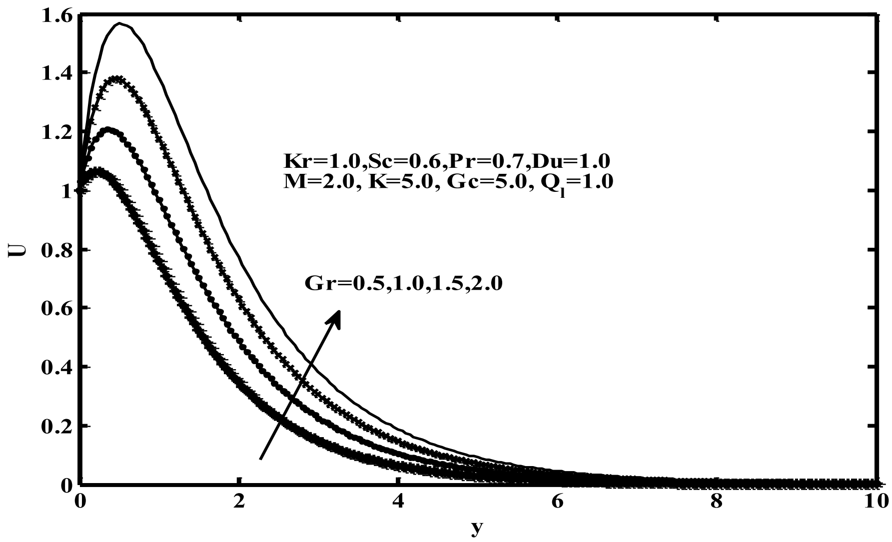

Figure (7): Velocity Profiles for different values of Gr

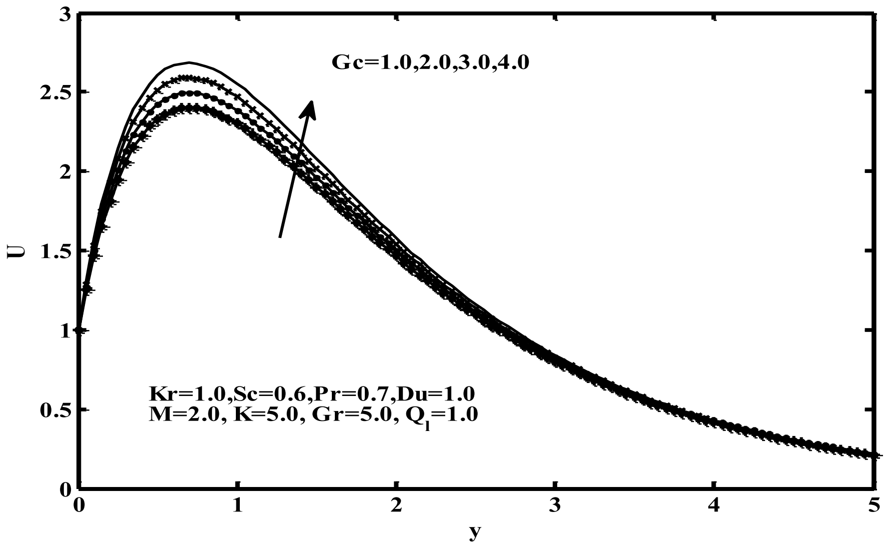

Figure (8); Velocity Profiles for different values of Gc

The effect of radiation absorption shown in Fig.9. We have observed that an increase of radiation absorption the velocity decreases. The effect of radiation absorption shown in Fig. 10. Observed that an increase of radiation absorption the temperature decreases.

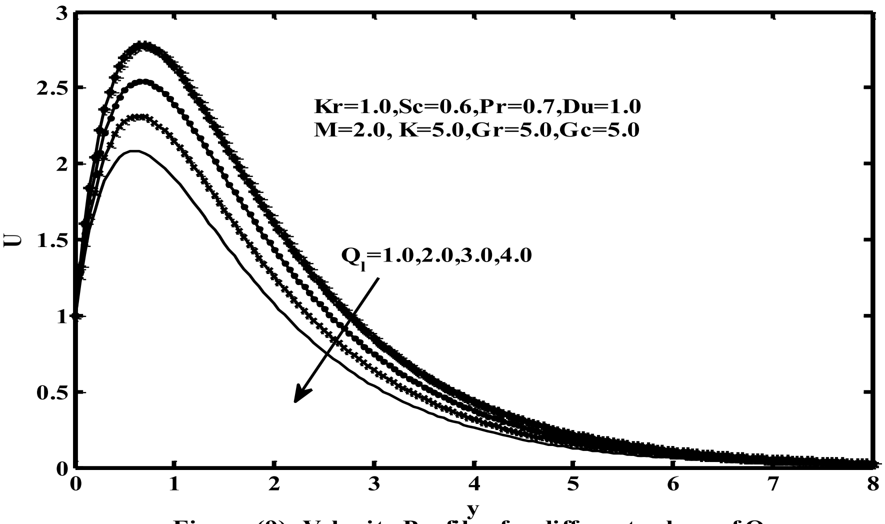

Figure (9): Velocity Profiles for different values of Q_l

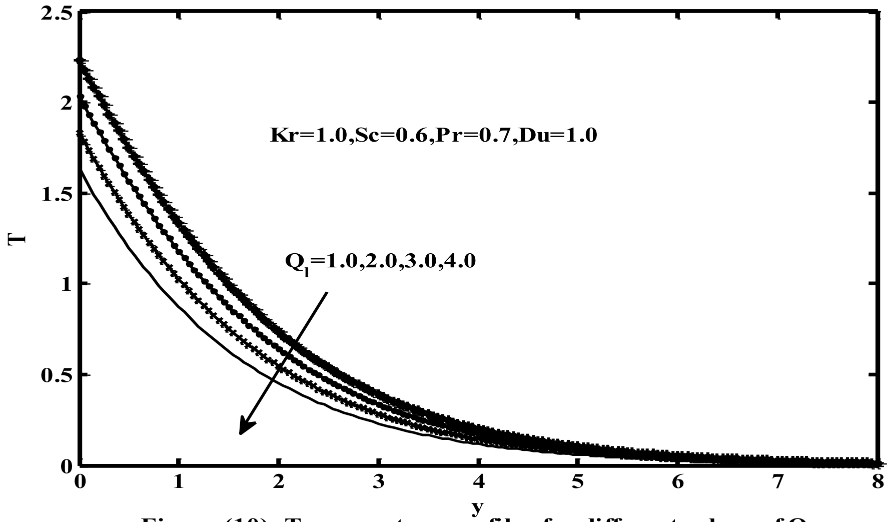

Figure (10): Temeperature profiles for different values of Q_l

The temperature profiles for Dufour parameter observed in Fig.11, it indicates the temperature increases with increases in Dufour parameter. With respect to Schmidt number Prandtl number and Chemical reaction parameter shown from Figs. 12 to 14. We find that that the temperature decreases with increases in the above parameters.

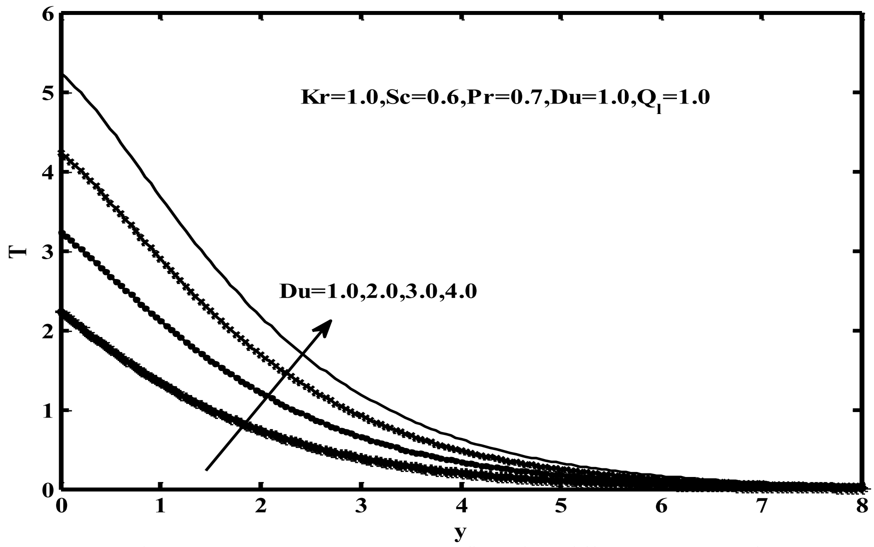

Figure (11): Temperature Profiles for different values of Du

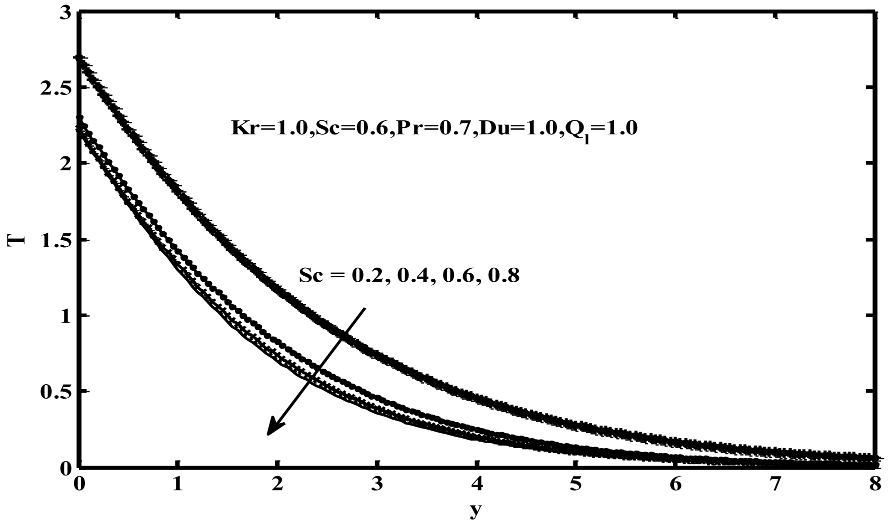

Figure (12): Temperature Profiles for different values of Sc

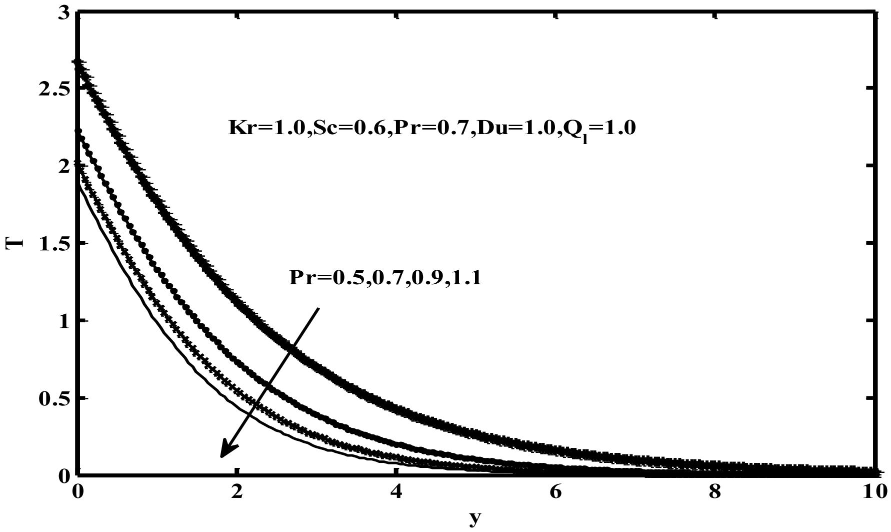

Figure (13): Temperature Profiles for different values of Pr

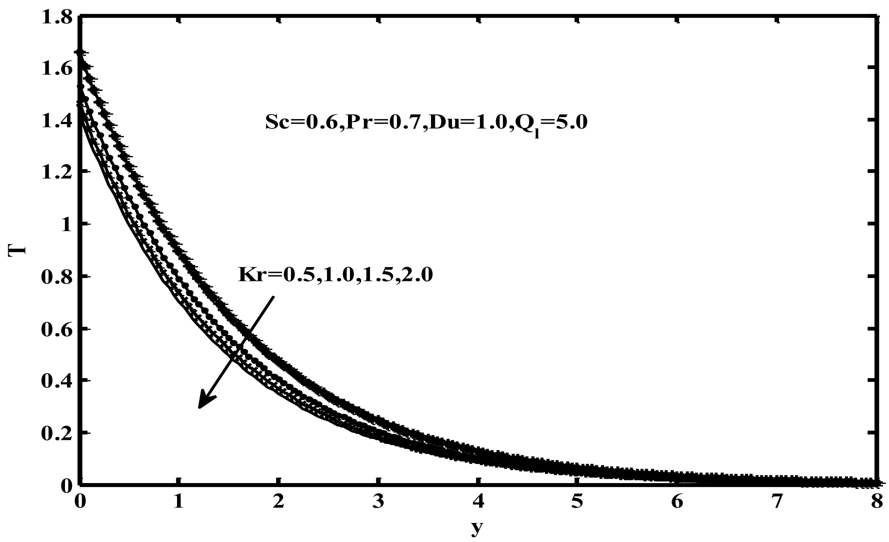

Figure (14): Temperature Profiles for different values of Kr

From Fig. 15, the effect of chemical reaction parameter on concentration is presented. As chemical reaction parameter increases the concentration decreases. From Fig. 16, the variations in concentration profiles for different values of Schmidt number. From this figure it is noticed that concentration decreases as Schmidt number increases. Physically it is consistent with fact that Schmidt number is a dimensionless number defined as the ratio of momentum diffusivity and mass diffusivity and is used to characterize fluid flows in which there are simultaneous momentum and mass diffusion convection processes as in the present problem, near the vicinity of the plate concentration appears to be very high, whereas it reaches to the stationary position for away from the surface.

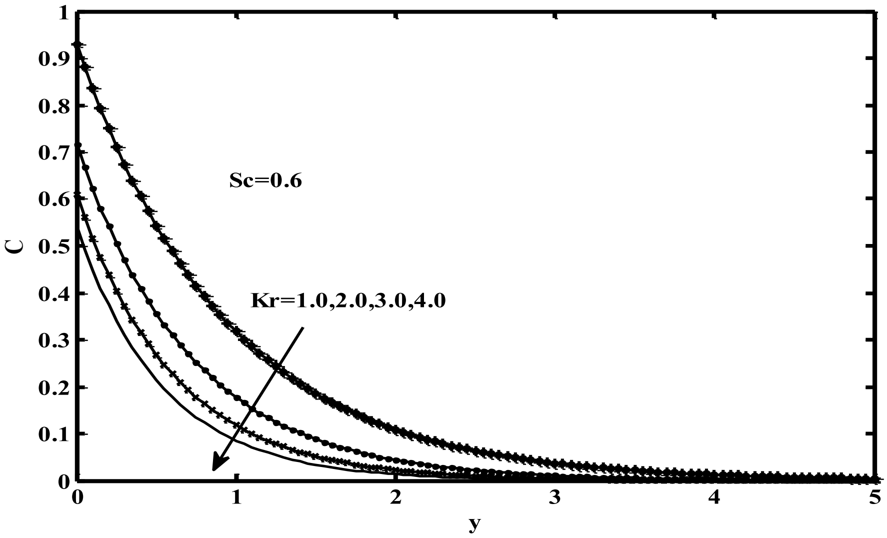

Figure (15): Concentration Profiles for different values of Kr

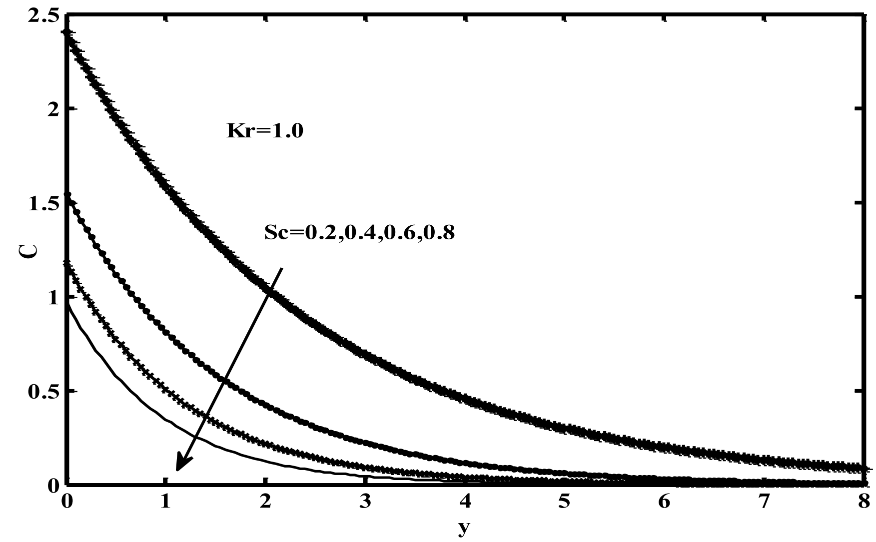

Figure (16): Concentration Profiles for different values of Sc

5. CONCLUSIONS

An analytical model has been developed to investigate MHD flow along a vertical surface under the influence of chemical reactions, Dufour effect, and radiation absorption. Key findings include:

- Velocity profiles diminish with increasing magnetic intensity and Schmidt number.
- Radiation absorption leads to a notable decrease in both velocity and temperature.
- Temperature rises with Dufour number but decreases with Prandtl number and chemical reaction intensity.
- Species concentration is inversely related to chemical reaction strength and Schmidt number.
- This study offers insights into optimizing thermal systems influenced by MHD and radiative phenomena in chemically reactive environments.

APPENDIX

$$\beta=\left(M+\frac{1}{K}\right),\ m_2=-\left(\frac{Sc+\sqrt{Sc^2+4KrSc}}{2}\right),\ m_4=-(\Pr)$$

$$m_6=-\left(\frac{1+\sqrt{1+4\beta}}{2}\right),\ J_1=\left(\frac{Q_l\Pr}{m_2^3+\Pr m_2{}^2}\right),J_2=\left(\frac{Du\,m_2\Pr}{m_2^2+\Pr m_2}\right)$$

$$J_3=-\left(\frac{1+m_2J_1+m_2J_2}{m_4}\right),\ A_1=-\left(\frac{Gr\left(J_1+J_2\right)}{m_2^2+m_2-\beta}\right),A_2=-\left(\frac{GrJ_3}{m_4^2+m_4-\beta}\right)$$

$$A_3=\frac{1}{m_2}\left(\frac{Gc}{m_2^2+m_2-\beta}\right),A_4=\left(1-A_1-A_2-A_3\right)$$

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