

# MHD Flow from a Vertical Porous Plate in presence of Heat Source

## ABSTRACT

**Aim:** With a heat source present, this analytical study aims to examine the thermal radiation affects the unsteady MHD free convective mass transfer flow through a semi-infinite vertical porous plate with a changing suction velocity.

**Study design:** On this plate, a uniform transverse magnetic field is applied perpendicularly. The non-dimensional governing equations are resolved by applying a simple perturbation technique.

**Place and Duration of Study:** Department of Mathematics, The Assam Royal Global University, Guwahati, Assam between January 2024 to August 2024

**Methodology:** We allow an infinite vertical porous plate to be passed by a viscous, incompressible fluid that is optically thin. The X-axis is introduced along the infinite vertical plate, the Y-axis is normal to the plate, and the Z-axis is along the width of the plate in a Cartesian coordinate system  $(x',y',z')$ . At the beginning, the fluid and plate were both at the same temperature  $(T'_{\infty})$  and concentration  $(C'_{\infty})$  throughout. The concentration level at the plate increased to  $C'_w$  at time  $t' > 0$ , and the plate temperature was abruptly increased to  $T'_w$ . The plate is subjected to a normal magnetic field that is consistent. The semi-infinite plane surface assumptions cause all the flow variables, with the exception of pressure, to be functions of only  $y'$  and  $t'$ .

**Results:** When the Grashof number  $Gr$  rises, the fluid velocity increases, but when the Hartmann number  $M$  rises, it decreases. In the presence of a heat source  $S$ , the fluid temperature drops as the radiation parameter  $Q$  and Prandtl number  $Pr$  grow. When the Soret number  $(Sr)$  increases, the species concentration at the boundary layer increases, but when the chemical reaction parameter  $(Kr)$  increases, it drops.

**Conclusion:** From the work we have concluded that in presence of heat source, the fluid temperature drops with the increment of Prandtl number and Radiation parameter.

*Keywords: Magnetohydrodynamics, thermal radiation, free convection, porosity*

**1. INTRODUCTION:** The study of electrically conducting fluid dynamics in the presence of magnetic fields is known as magnetohydrodynamics. In 1970, Hannes Alfvén won the Nobel Prize in Physics for founding the science of MHD. The basic idea of MHD is that a flowing conductive fluid can induce current in it, which in turn applies forces to the fluid and modifies the magnetic field. Numerous scientific domains have found use for MHD, which has motivated numerous scientists to pursue research on it. Geophysics, plasma physics, and astrophysics

subjects like magneto-convection and MHD turbulence are among the subjects covered in MHD. It is important for biomedical science and biomedical engineering as well. Natural convection is a heat-transfer process where fluid motion is not produced by Soret effect or thermal diffusion is the process of transfer of mass due to combined effect of concentration and temperature gradient. Many industrial and environmental processes such as in evaporation from large open water reservoirs, heating and cooling chambers etc.

The degree to which a material blocks light from flowing through it is known as its optical thickness. The dimensions and physical characteristics of the material determine its optical thickness. It is a dimensionless quantity represented by the symbol  $\tau$ . The gas is considered optically thick if  $\tau \gg 1$ , and optically thin if  $\tau \ll 1$ . A gray gas is one whose optical thickness is unaffected by the electromagnetic radiation's wave number. If not, the gas is referred to as non-gray gas. Non-gray gases are frequently encountered in the environment.

**Comment [S1]:** This paragraph is not addressing thermal radiation effect, make a good paragraph and citations of literature for the purpose

Survey of literature is an essential ingredient of research work. Everyone has to rely on it to understand and develop the concept to analyse the subject of research. Bejan et al. [1], Ahmed and Choudhury [8], Sattar [10] and many others have studied MHD free convective heat and mass transfer flow in a porous medium. Mythere and Balamurugan [3] have considered MHD free convective flow with thermal diffusion due to importance of Soret effect in fluid motion. Coogley et al. [2] have researched on Differential approximation for radiative heat transfer in a Gray gas near equilibrium. Pal and Talukdar [5] have analysed MHD convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction by perturbation technique. Similarly, Cookey et al. [4], Ibrahim et al. [6] and many other scientists have analysed the radiation effect of MHD flows. Balamurugan et al. [7] have researched on unsteady MHD free convective flow with time dependent suction and chemical reaction in a slip flow regime. N. Ahmed [9] analysed the effect of chemical reaction on a transient MHD flow past a suddenly started infinite vertical plate with thermal diffusion and radiation.

**Comment [S2]:** Not necessary so remove

**2. MATHEMATICAL FORMULATION:** Allow an infinite vertical porous plate to be passed by a viscous, incompressible fluid that is optically thin. The X-axis is introduced along the infinite vertical plate, the Y-axis is normal to the plate, and the Z-axis is along the width of the plate in a Cartesian coordinate system  $(x', y', z')$ . At the beginning, the fluid and plate were both at the same temperature  $(T'_{\infty})$  and concentration  $(C'_{\infty})$  throughout. The concentration level at the plate increased to  $C'_{\infty}$  at time  $t' > 0$ , and the plate temperature was abruptly increased to  $T'_{\infty}$ . The plate is subjected to a normal magnetic field that is consistent. The semi-infinite plane surface assumptions cause all the flow variables, with the exception of pressure, to be functions of only  $y'$  and  $t'$ .

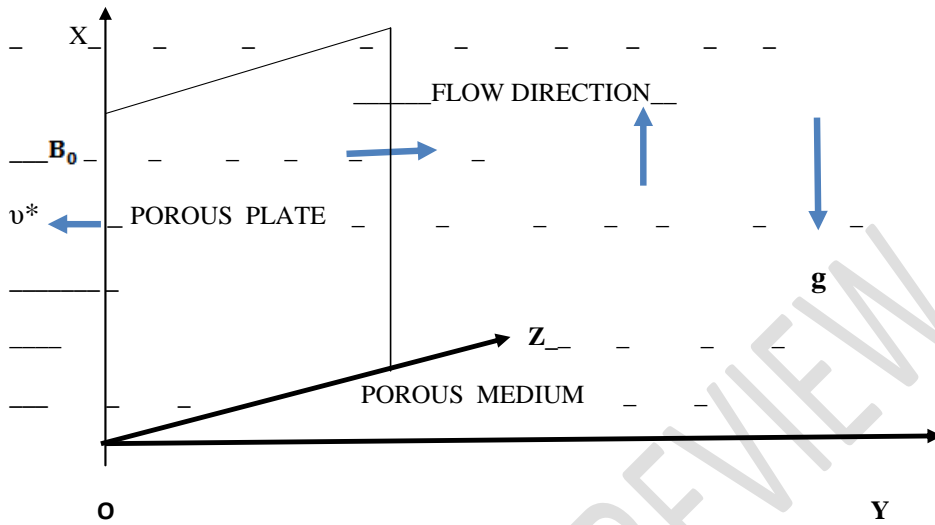


Figure 1. Physical Configuration

### Governing equations

#### Continuity equation-

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

#### Momentum equation-

$$\frac{\partial u'}{\partial \tau'} + v' \frac{\partial u'}{\partial y'} = g\beta(T' - T'_{\infty}) + g\beta^*(C' - C'_{\infty}) + \nu \frac{\partial^2 u'}{\partial y'^2} - \frac{\nu}{k'} u' - \frac{\sigma B_0^2}{\rho} u' \quad (2)$$

#### Energy equation-

$$\frac{\partial T'}{\partial \tau'} + v' \frac{\partial T'}{\partial y'} = \frac{k_1}{\rho c_p} \frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho c_p} \frac{\partial q_r}{\partial y'} + S^*(T - T_{\infty}) \quad (3)$$

#### Species continuity equation-

$$\frac{\partial C'}{\partial \tau'} + v' \frac{\partial C'}{\partial y'} = D \frac{\partial^2 C'}{\partial y'^2} + D_1 \frac{\partial^2 T'}{\partial y'^2} - K_1(C' - C'_{\infty}) \quad (4)$$

The corresponding boundary conditions are:

$$\left. \begin{aligned} t > 0, u' = 0, T' = T'_{\infty} + (T'_w - T'_{\infty})(1 + \varepsilon e^{i\omega' t'}), C' = C'_w \text{ at } y' = 0 \\ u' \rightarrow 0, T' \rightarrow T'_{\infty}, C' \rightarrow C' \text{ at } y' \rightarrow \infty \end{aligned} \right\} \quad (5)$$

with usual meaning of the symbols.

According to Coogley's model, the radiative heat flux in optically thin non-gray gas near equilibrium is specified by

$$\frac{\partial q_r}{\partial y'} = 4I(T' - T'_{\infty}), \text{ where } I = \int_0^{\infty} (K_{\lambda})_w \left( \frac{\partial \varepsilon_{\lambda b}}{\partial T'} \right)_w d\lambda \quad (6)$$

Using (6) in (3) we get,

$$\frac{\partial T'}{\partial \tau'} + v' \frac{\partial T'}{\partial y'} = \frac{K_1}{\rho C_p} \frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho C_p} 4I(T' - T'_{\infty}) \quad (3.1)$$

It is seen from equation (1) that  $v'$  is a constant. Assuming the suction velocity to be oscillatory we have

$$v' = -v_0(1 + \varepsilon A e^{i\omega \tau}) \quad (7)$$

where  $\varepsilon, A$  are small such that  $\varepsilon A \ll 1$ .

The non-dimensional quantities for making the governing equations in dimensionless form are-

$$y = \frac{v_0 y'}{v}, u = \frac{u'}{v_0}, t = \frac{t' v_0^2}{4\nu}, T = \frac{T' - T'_{\infty}}{T'_w - T'_{\infty}}, C = \frac{C' - C'_{\infty}}{C'_w - C'_{\infty}}, Sc = \frac{\nu}{D}, v = \frac{v'}{v_0}, Gr = \frac{g\beta v(T'_w - T'_{\infty})}{v_0^3},$$

$$Gc = \frac{g\beta^* v(C'_w - C'_{\infty})}{v_0^3}, \omega = \frac{4\nu \omega'}{v_0^2}, M = \frac{\sigma B_0^2 \nu}{\rho v_0^2}, K = \frac{K' v_0^2}{\nu^2}, Sr = \frac{D_1(T'_w - T'_{\infty})}{\nu(C'_w - C'_{\infty})}, Pr = \frac{\mu C_p}{K_1},$$

$$Q = \frac{4I\nu}{\rho C_p v_0^2}, Kr = \frac{\nu K_1}{v_0^2}, S = \frac{S^* v^2}{K_T v_0^2}$$

Using the above non-dimensional quantities in the equations (2), (3.1) and (4), the governing equation reduces to

$$\frac{1}{4} \left( \frac{\partial u}{\partial t} \right) - (1 + \varepsilon A e^{i\omega t}) \frac{\partial u}{\partial y} = GrT + GcC + \frac{\partial^2 u}{\partial y^2} - \left( M + \frac{1}{K} \right) u \quad (8)$$

$$\frac{1}{4} \left( \frac{\partial T}{\partial t} \right) - (1 + \varepsilon A e^{i\omega t}) \frac{\partial T}{\partial y} = \frac{1}{Pr} \frac{\partial^2 T}{\partial y^2} - QT + \frac{S}{Pr} T \quad (9)$$

$$\frac{1}{4} \left( \frac{\partial C}{\partial t} \right) - (1 + \varepsilon A e^{i\omega t}) \frac{\partial C}{\partial y} = \frac{1}{Sc} \frac{\partial^2 C}{\partial y^2} + Sr \frac{\partial^2 T}{\partial y^2} - KrC \quad (10)$$

The corresponding boundary conditions are-

$$\left. \begin{aligned} t > 0, u = 0, T = T_W = 1 + \varepsilon e^{i\omega t}, C = 1 \text{ at } y = 0 \\ u \rightarrow 0, T \rightarrow 0, C \rightarrow 0 \text{ at } y \rightarrow \infty \end{aligned} \right\} \quad (11)$$

### 3. METHOD OF SOLUTION

The above system of partial differential equation is reduced to ordinary differential equation by taking the velocity, temperature and concentration respectively as-

$$\left. \begin{aligned} u(y, t) &= u_0(y) + \varepsilon e^{i\omega t} u_1(y) + O(\varepsilon^2) \\ T(y, t) &= T_0(y) + \varepsilon e^{i\omega t} T_1(y) + O(\varepsilon^2) \\ C(y, t) &= C_0(y) + \varepsilon e^{i\omega t} C_1(y) + O(\varepsilon^2) \end{aligned} \right\} \quad (12)$$

Substituting (12) in the equations (8) to (10) and equating the harmonic and non-harmonic terms, and also neglecting the higher order terms of  $\varepsilon$ , we get

$$u_0'' + u_0' - \left( M + \frac{1}{K} \right) u_0 = -GrT_0 - GcC_0 \quad (13)$$

$$u_1'' + u_1' - \left( M + \frac{1}{K} + \frac{i\omega}{4} \right) u_1 = -Au_0' - GrT_1 - GcC_1 \quad (14)$$

$$T_0'' + PrT_0' - PrQT_0 + ST_0 = 0 \quad (15)$$

$$T_1'' + Pr T_1' - \left(Q + \frac{i\omega}{4}\right) Pr T_1 + S T_1 = -Pr A T_0' \quad (16)$$

$$C_0'' + Sc C_0' - Sc Kr C_0 = -Sc Sr T_0'' \quad (17)$$

$$C_1'' + Sc C_1' - \left(Kr + \frac{i\omega}{4}\right) Sc C_1 = -ASc C_0' - Sr Sc T_1'' \quad (18)$$

And the corresponding boundary conditions are-

$$t > 0, u_0 = u_1 = 0, T_0 = T_1 = 1, C_0 = 1, C_1 = 0 \text{ at } y = 0 \quad (19)$$

$$u_0 = u_1 \rightarrow 0, T_0 = T_1 \rightarrow 0, C_0 = C_1 \rightarrow 0 \text{ as } y \rightarrow \infty$$

By utilizing the perturbation technique to solve equations (13) through (18) and applying boundary conditions (19), the corresponding solutions for velocity, temperature, and concentration are

$$u = (A_6 + A_7)e^{-m_{10}y} - A_6 e^{-m_2y} - A_7 e^{-m_6y} + \varepsilon e^{i\omega t} [(A_8 + A_9 + A_{10} - A_{11} - A_{12})e^{-m_{12}y} - A_8 e^{-m_2y} - A_9 e^{-m_4y} - A_{10} e^{-m_6y} + A_{11} e^{-m_8y} + A_{12} e^{-m_{10}y}] \quad (20)$$

$$T = e^{-m_2y} + \varepsilon e^{i\omega t} [(1 - A_1)e^{-m_4y} + A_1 e^{-m_2y}] \quad (21)$$

$$C = (1 + A_2)e^{-m_6y} - A_2 e^{-m_2y} + \varepsilon e^{i\omega t} [-(A_3 + A_4 + A_5)e^{-m_8y} + A_3 e^{-m_2y} + A_4 e^{-m_4y} + A_5 e^{-m_6y}] \quad (22)$$

### Skin Friction-

The shear stress in the wall is quantified by the relation-

$$\tau = \left. \frac{\partial u}{\partial y} \right|_{y=0}$$

$$= -(A_6 + A_7)m_{10} + A_6 m_2 + A_7 m_6 + \varepsilon e^{i\omega t} [-(A_8 + A_9 + A_{10} - A_{11} - A_{12})m_{12} + A_8 m_2 + A_9 m_4 + A_{10} m_6 - A_{11} m_8 - A_{12} m_{10}]$$

$$(23)$$

### Nusselt number-

The rate of heat transfer at the plate in terms of the Nusselt number based on Fourier's law of heat conduction is expressed as-

$$\begin{aligned} Nu &= \left. \frac{\partial T}{\partial y} \right]_{y=0} \\ &= -m_2 + \varepsilon e^{i\omega t} [-(1 - A_1)m_4 - A_1m_2] \end{aligned} \quad (24)$$

### Sherwood number-

The rate of concentration in terms of Sherwood number ( $Sh$ ) is given by the relation-

$$\begin{aligned} Sh &= \left. \frac{\partial C}{\partial y} \right]_{y=0} \\ &= -(1 + A_2)m_6 + A_2m_2 + \varepsilon e^{i\omega t} [(A_3 + A_4 + A_5)m_8 - A_3m_2 - A_4m_4 - A_5m_6] \end{aligned} \quad (25)$$

where,

$$\begin{aligned} m_2 &= \frac{Pr + \sqrt{Pr^2 - 4(S - QPr)}}{2}, \\ m_4 &= \frac{Pr + \sqrt{Pr^2 - 4\{S - (Q + \frac{i\omega}{4})Pr\}}}{2}, \quad m_6 = \frac{Sc + \sqrt{Sc^2 + 4ScKr}}{2}, \\ m_8 &= \frac{Sc + \sqrt{Sc^2 + (4Kr + i\omega)Sc}}{2}, \quad m_{10} = \frac{1 + \sqrt{1 + 4\left(M + \frac{1}{k}\right)}}{2}, \quad N = M + \frac{1}{k} + \frac{i\omega}{4}, \\ m_{12} &= \frac{1 + \sqrt{1 + 4N}}{2}, \quad A_1 = \frac{PrAm_2}{m_2^2 - Prm_2 - \left(Q + \frac{i\omega}{4}\right)Pr + S}, \quad A_2 = \frac{ScSrm_2^2}{m_2^2 - Scm_2 - ScKr} \end{aligned}$$

$$A_3 = \frac{(SrA_1 - AA_2)Scm_2}{f_1(m_2)}, A_4 = \frac{SrSc(1 - A_1)m_4}{f_1(m_4)}, A_5 = \frac{AScm_6(1 + A_2)}{f_1(m_6)},$$

$$f_1(x) = x^2 - Scx - \left(Kr + \frac{i\omega}{4}\right)Sc, A_6 = \frac{Gr - GcA_2}{f_2(m_2)}, A_7 = \frac{Gc(1 + A_2)}{f_2(m_6)}, f_2(x) = x^2 - x - \left(M + \frac{1}{k}\right),$$

$$A_8 = \frac{AA_6m_2 + GrA_1 + GcA_3}{f_3(m_2)}, A_9 = \frac{Gr(1 - A_1) + GcA_4}{f_3(m_4)}, A_{10} = \frac{AA_7m_6 + GcA_5}{f_3(m_6)},$$

$$A_{11} = \frac{Gc(A_3 + A_4 + A_5)}{f_3(m_8)}, A_{12} = \frac{A(A_6 + A_7)m_{10}}{f_3(m_{10})}, f_3(x) = x^2 - x - N.$$

#### 4. RESULTS AND DISCUSSIONS:

The physical depth of the problem is analyzed by studying graphically the effects of various parameters like Thermal Grashof number ( $Gr$ ), Hartmann number ( $M$ ), Radiation parameter ( $Q$ ) etc. on velocity, temperature, concentration, Nusselt number and Sherwood number which are shown in Figure 2-10.

**Comment [S3]:** Precisely state all parameters considered in the work

Figure 2 illustrates how velocity rises as  $Gr$  increases. As seen in Figure 3, fluid flow in the presence of a magnetic field generates the resistive Lorentz force, which slows the fluid's speed. As radiation parameter  $Q$  rises, Figure 4 illustrates how the temperature's magnitude decreases. Figure 5 shows that a rise in pressure causes the fluid temperature to decrease. This is because heat diffuses from the heated plate more quickly with smaller values of  $Pr$  than with higher values of  $Pr$  since smaller values of  $Pr$  improve the thermal conductivities. It is observed that the rise in temperature reduces the species concentration in the boundary layer.

Figure 8 shows that when Hartmann number  $M$  increases, the skin friction magnitude decreases. As Figure 9 illustrates, the rate of heat transfer  $Nu$  increases significantly with increasing radiation parameter  $Q$ . Figure 10 shows that the radiation parameter  $Q$  has an effect on the rate of mass transfer  $Sh$  at the plate.

**Comment [S4]:** The discussion should explicitly explain the flow profiles from the graphs.

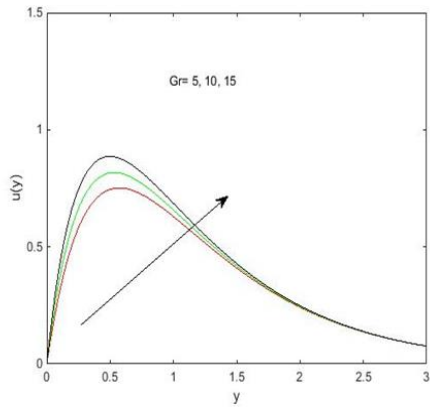


Figure 2. Velocity profile versus  $y$  for variation in  $Gr$  when  $Q=5$ ,  $M=20$ ,  $K=20$ ,  $Sc=0.7$ ,  $Sr=10$ ,  $Gc=5$ ,  $Kr=1$ ,  $Pr=0.71$ ,  $\epsilon=0.01$ ,  $\omega=2$ ,  $A=0.01$ ,  $t=0.2$

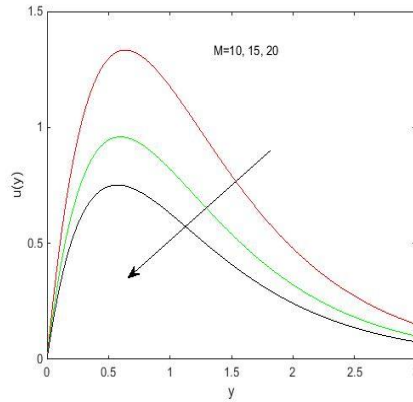


Figure 3. Velocity profile versus  $y$  for variation in  $M$  when  $Q=5$ ,  $K=20$ ,  $Sc=0.7$ ,  $Sr=10$ ,  $Gc=5$ ,  $Kr=1$ ,  $Gr=5$ ,  $Pr=0.71$ ,  $\epsilon=0.01$ ,  $\omega=2$ ,  $A=0.01$ ,  $t=0.2$

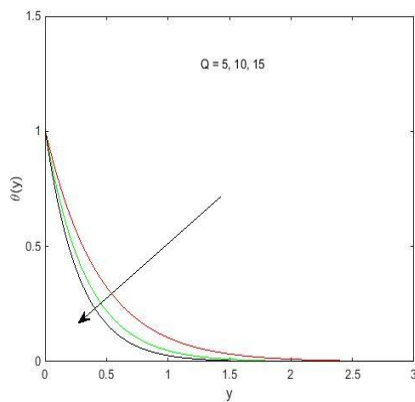


Figure 4. Temperature profile versus  $y$  for variation in  $Q$  when  $Pr=0.71$ ,  $\epsilon=0.01$ ,  $\omega=2$ ,  $A=0.01$ ,  $t=0.2$ ,  $S=5$

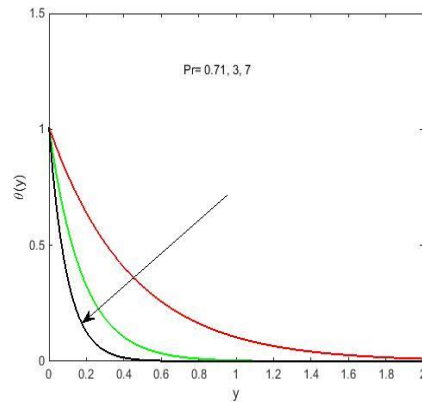


Figure 5. Temperature profile versus  $y$  for variation in  $Pr$  when  $Q=5$ ,  $\epsilon=0.01$ ,  $\omega=2$ ,  $A=0.01$ ,  $t=0.2$ ,  $S=5$

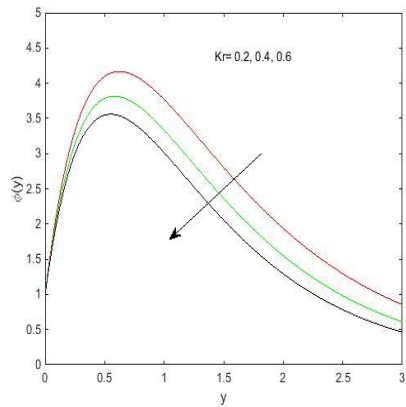


Figure 6. Concentration profile versus  $y$  for variation in  $Kr$  when  $Pr=0.71, Sr=10, Sc=0.7, Q=5, \epsilon=0.01, \omega=2, A=0.01$

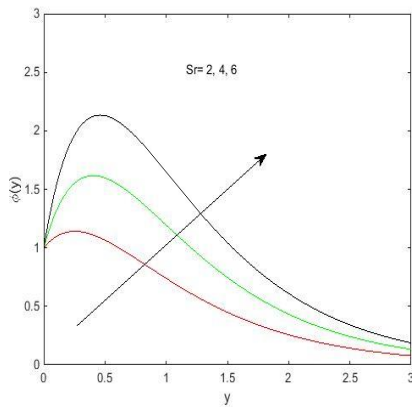


Figure 7. Concentration profile versus  $y$  for variation in  $Sr$  when  $Pr=0.71, Kr=1, Sc=0.7, Q=5, \epsilon=0.01, \omega=2, A=0.01$

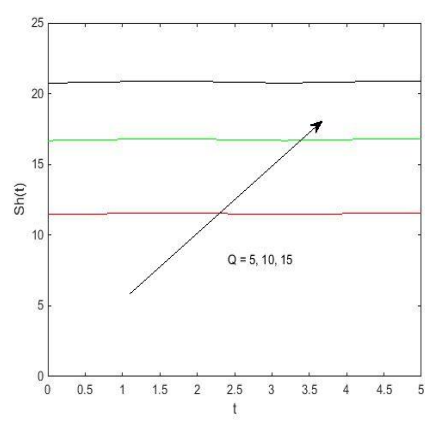


Figure 8. Skin friction versus  $t$  for variations in  $M$  when  $Q=5, Gc=5, Sr=10, Sc=0.7, Gr=5, K=20, Pr=0.71, Kr=1, \epsilon=0.01, \omega=2, A=0.01$

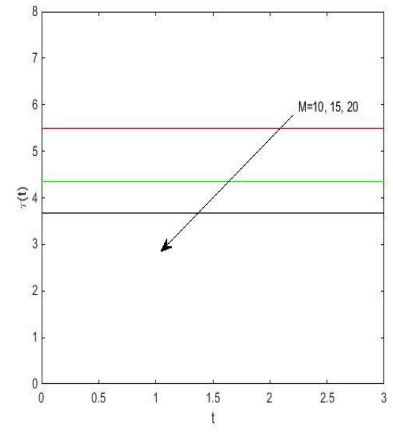


Figure 9. Nusselt number versus  $t$  for variation in  $Q$  when  $Pr=0.71, \epsilon=0.01, \omega=2, A=0.01$

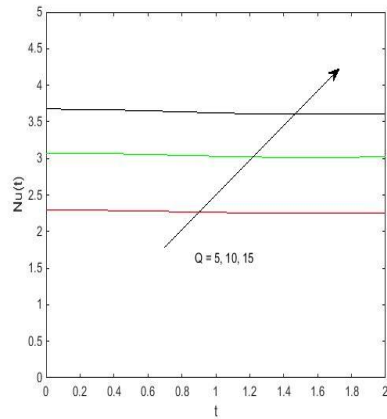


Figure 10. Sherwood number versus  $t$  for variation in  $Q$  when  $Sr=10$ ,  $Sc=0.7$ ,  $Pr=0.71$ ,  $Kr=1$ ,  $\varepsilon=0.01$ ,  $\omega=2$ ,  $A=0.01$

**Comment [S5]:** The graph 8 - 10 shows no or less effects of the parameters on the skin friction, nusselt and shearwood numbers, provide discussion of the less effects.

## CONCLUSIONS

- i. When the Grashof number  $Gr$  rises, the fluid velocity increases, but when the Hartmann number  $M$  rises, it decreases
- ii. In the presence of a heat source  $S$ , the fluid temperature drops as the radiation parameter  $Q$  and Prandtl number  $Pr$  grow.
- iii. When the Soret number ( $Sr$ ) increases, the species concentration at the boundary layer increases, but when the chemical reaction parameter ( $Kr$ ) increases, it drops.

## SCOPE FOR FUTURE WORK

The project can be extended by adding some terms to the governing equations and to find its applications in scientific fields.

## NOMENCLATURE

$u'$  = Component of velocity along x-axis.

$v'$  = Component of velocity along y-axis.

$t'$  = Time.

$t$  = Non-dimensional time.

$\rho$  = Density of the fluid.

$g$  = Acceleration due to gravity.

$v$  = Velocity of the fluid.

$v_0$  = Scale of the suction velocity.

$\sigma$  = Electrical conductivity.

$\nu$  = Kinematic viscosity.

$\beta$  = Coefficient of volume expansion of the fluid.

$\beta^*$  = Coefficient of thermal expansion with concentration.

$B_0$  = Magnetic induction parameter.

$T$  = Temperature of the fluid.

$T'_\infty$  = Temperature of the fluid far away from the plate.

$T'_w$  = Temperature of the plate.

$C$  = Species Concentration of the fluid.

$C'_\infty$  = Species Concentration of the fluid far away from the plate.

$C'_w$  = Species Concentration of the fluid near the plate.

$\mu$  = Coefficient of viscosity.

$C_p$  = Specific heat at constant pressure.

$K_T$  = Thermal conductivity.

$D$  = Chemical molecular diffusivity.

$D_1$ = Thermal diffusion ratio.

$M$ = Hartmann number.

$Sr$ = Soret number.

$Sc$ = Schmidt number.

$Gr$ =Thermal Grashof number.

$Gc$ = Solutal Grashof number.

$Pr$ = Prandtl number.

$Q$ = Radiation parameter.

$Kr$ = Chemical reaction parameter.

$q_r$ = Radiative heat flux.

$K$ = Porosity parameter.

$K_1$  = First order chemical reaction rate constant

$K'$  = Permeability of the porous media.

$S^*$ = Coefficient of heat source.

$S$ = Heat source parameter.

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