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CHEMICALLY REACTING MAGNETO-HYDRODYNAMICS (MHD) FLUID FLOW THROUGH A POROUS MEDIUM

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Abstract: This paper considered and investigated the effects of chemically reacting Fluid flow through a porous medium in a Magnetic field as a magneto-hydrodynamics fluid flow through a porous medium. We developed a mathematical model for the flow and using perturbation method, the modeled partial differential equations were reduced to a system of ordinary differential equations and solved. The geometry of the problem was considered where the x-axis is taken in the vertical direction along the plate while y-axis is normal to the plate so that all the characteristics of the fluid are independent of the variable x. The impact of Chemical reaction, Magnetic intensity, Prandtl number, Schmidt number, porosity and thus permeability of the physical parameters were investigated on velocity, temperature, and concentration profiles. More so, the impacts of the same parameters were investigated on the skin-friction, Nusselt number, and Sherwood number. The results showed that growing magnetic intensity leads to decrease in velocity and skin-friction of the flow field at every point, increase in chemical reaction and Schmidt number leads to decrease in temperature and concentration at every point of the flow field. An increase in Prandtl number, Magnetic intensity, and Permeability shows no effect on concentration profile at every point of the flow field.

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1. INTRODUCTION

It has been observed that the chemically reacting fluid flow in a magnetic field through a porous medium considered as a Magneto-hydrodynamic (MHD) fluid flow through a porous medium has gotten remarkable importance in many technical fields, so that many scientists and technologists are taking keen interest in the study of fluid flow so that their results so obtained may be applied with great accuracy in the respective fields. In this context, we have gone through the contributions made by many great researchers and their achievements in this field in a chronological order so that some new mathematical models governing such motion of a fluid may be innovated and improved results in this study based on the adopted theories and Mathematical methods can be found. We observed that, Chambre & Yonug [1] discussed the diffusion of a chemically reactive species. Also, the effect of magnetic field, heat, and mass transfer on unsteady two-dimensional laminar flow of a viscous incompressible fluid past a semi-infinite moving vertical porous plate with variable suction in the presence of homogeneous first order chemical reaction and temperature dependent heat generation was studied by [2]. Mbeledogu and Ogulu [3] presented the solution of unsteady hydromagnetic natural convection heat and mass transfer flow of a rotating fluid past a vertical porous plate in the presence of first order chemical reaction and radiative heat transfer. Pal & Mondal [4] in their pioneer work studied the effects of variable thermal conductivity, thermal diffusion, and diffusion thermo on mass transfer and MHD non – Darcy mixed convection heat over a non – linear stretching sheet with chemical reaction. Khan et al. (2014) proposed numerically MHD laminar boundary layer flow over a wedge because of heat generation, chemical reaction, and thermal radiation. Chamkha and Ahmed [6] studied on similarity solution for unsteady MHD flow near a stagnation point of a three – dimensional porous body with mass

transfer and heat, chemical reaction, and heat generation / absorption. Rao et al. [7] analyzed an unsteady MHD free convection heat and mass transfer flow past a semi-infinite vertical permeable moving plate with chemical reaction and solet effects, heat absorption, and radiation. Srinivasachanya and Reddy [7] made a detailed report on free convection in a non – Newtonian power law fluid over a saturated porous medium with chemical reactions and radiation effects. In this work, we investigated the chemically reacting flow through a porous medium in a magnetic field as a MHD fluid flow through a porous medium. The momentum, energy and diffusion equations that govern the flow field are solved using perturbation method.

2. MATHEMATICAL FORMULATION OF THE PROBLEM

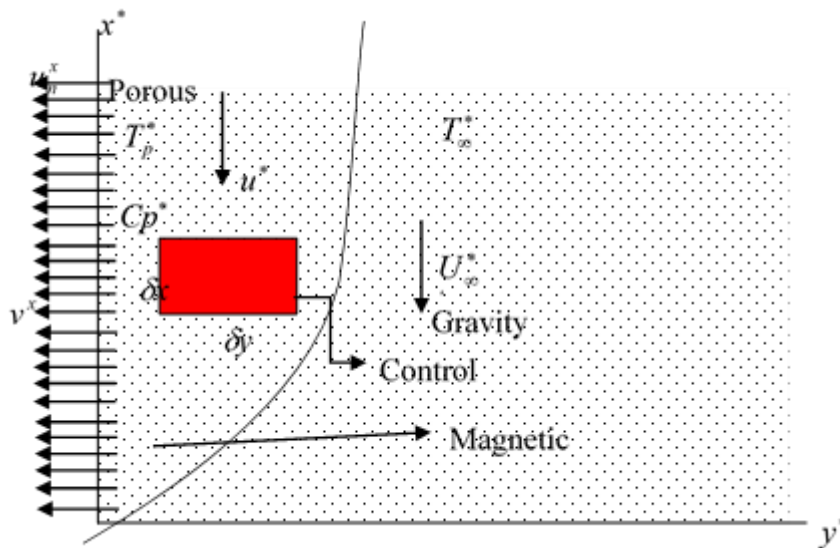


Fig. 2.1, Geometry of the flow problem

In fig.1.1 above, we considered unsteady, two-dimensional, MHD natural convection with chemically reacting fluid flow over a porous vertical plate. The x^* -axis is taken along the vertical plate while the y^* -axis is perpendicular to the plate. A steady magnetic field is applied in the direction normal to the plate. By the application of magnitude analysis on the Navier-Stokes's equation, the MHD term is derived. The properties of fluid are assumed to be constant but the

influence of temperature on density variation has been considered in the body force. For the fact that the plate is vertical and continuous in x^* - direction, all physical parameters depend only on y and t . Based on the above claim, the governing equations and boundary conditions for the flow field are given below as given by [9] are.

Continuity equation

$$\frac{\partial v^*}{\partial y^*} = 0, \quad (1)$$

Momentum equation

$$\begin{aligned} \frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = v \frac{\partial^2 u^*}{\partial y^{*2}} - v \frac{\phi u^*}{k^*} + g\beta(T^* - T_\infty^*) + g\beta^*(C^* - C_\infty^*) \\ - \frac{\sigma B_0^2 u^*}{\rho} - \frac{vu^*}{k^*}, \end{aligned} \quad (2)$$

Energy equation

$$\left(\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} \right) = \frac{k}{\rho C_p} \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{Q_0^*}{\rho C_p} (T^* - T_\infty^*) + Q_1^* (C^* - C_\infty^*) \quad [9], \quad (3)$$

Diffusion equation

$$\frac{\partial C^*}{\partial t^*} + \frac{v}{\phi} \frac{\partial C^*}{\partial y^*} = D \frac{\partial^2 C^*}{\partial y^{*2}} - \frac{K_1^*}{\phi} (C^* - C_\infty^*). \quad (4)$$

Subject to the boundary conditions.

$$\left. \begin{aligned} u^* = u_n^*, T^* = T_p^*, C^* = C_p^*, \text{ at } y^* = 0, \\ u^* = u^*(t), T^* \rightarrow T_\infty^*, C^* \rightarrow C_\infty^*, \text{ as } y \rightarrow \infty. \end{aligned} \right\} \quad (5)$$

The parameters of the model are described as:

Symbols	Meaning
v^*	Velocity in y- direction
u^*	Velocity in x- direction
t^*	Time
C_p^*	Concentration at the plate
C_∞^*	Concentration far away from the plate
T_p^*	Temperature at the plate
T_∞^*	Temperature far away from the plate
ρ	Fluid density
p	Pressure
B_0	Magnetic field
g	Gravitational acceleration
β^*	Expansion due to concentration
β	Expansion due to temperature
K_1^*	Chemical reaction parameter
K	Permeability parameter
T^*	Dimensional temperature
C	Dimensionless concentration
C^*	Dimensional concentration
ν	Kinematic viscosity
Pr	Prandtl number
Sc	Schmidt number
Gr	Thermal Grashof number
Gm	Modified Grashof number
C_f	Skin-friction

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Sh	Sherwood number
Q_1	Dimensionless volumetric flow rate
Q_1^*	Dimensional volumetric flow rate
Q_0	Dimensionless heat generation
Q_0^*	Dimensional heat generation
A	Dimensionless magnetic field parameter
μ	Fluid viscosity
u_n	Dimensional velocity at the plate
y_0	Scale of suction velocity
f	External body force
ω	Frequency of oscillation
p	Condition of the plate
∞	Free stream condition
$*$	Spatial coordinate along the plate

Considering the continuity equation 1, the far away velocity normal to the plate is a function of time only and can be taken in exponential form as,

$$v^* = -y_0(1 + \varepsilon f(t)), \quad (6)$$

where

$$f(t) = \ell^{i\omega t}.$$

Therefore, we have that (6) becomes

$$v^* = -y_0(1 + \varepsilon \ell^{i\omega t}).$$

The negative sign shows that the flow is towards the plate.

$\varepsilon(\varepsilon \ll 1)$ = a constant quantity.

We introduce the following dimensionless quantities and parameters.

$$\begin{aligned}
u &= \frac{u^* \phi}{y_0}, \quad v = \frac{v^* \phi}{y_0}, \quad y = \frac{y_0 y^*}{v}, \quad u_n = \frac{u_n^*}{y_0}, \quad T = \frac{T^* - T_\infty^*}{T_p^* - T_\infty^*}, \\
C &= \frac{C^* - C_\infty^*}{C_p^* - C_\infty^*}, \quad u(t) = \frac{u^*(t)}{y_0}, \quad t = \frac{y_0^2 t^*}{v}, \quad Sc = \frac{v}{D}, \\
Gr &= \frac{vg\beta\phi(T_p^* - T_\infty^*)}{y_0^3}, \quad Gm = \frac{vg\beta^* \phi(C_p^* - C_\infty^*)}{y_0^3}, \quad Pr = \frac{\mu C_p}{k}, \\
A &= \frac{\sigma B_0^2 v}{\rho y_0^2}, \quad k = \frac{k^* y_0^2}{v^2}, \quad Q_0 = \frac{Q_0^* v (C_p^* - C_\infty^*)}{\rho C_p y_0^2 (T_p^* - T_\infty^*) + T_\infty^*}, \\
Q_1 &= \frac{Q_1^* v (C_p^* - C_\infty^*)}{y_0^2 (T_p^* - T_\infty^*) + T_\infty^*}, \quad K_1 = \frac{K_1^* v (C_p^* - C_\infty^*)}{y_0^2 [(C_p^* - C_\infty^*) + C_\infty^*]}.
\end{aligned} \tag{7}$$

Applying these dimensionless quantities and parameters in equations (2-4), we obtained the following equations

$$\frac{\partial u}{\partial t} - (1 + \mathcal{E}f(t)) \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} - u \left(A + \frac{\phi}{k} + \frac{1}{k} \right) + GrT + GmC, \tag{8}$$

$$\frac{\partial T}{\partial t} - (1 + \mathcal{E}f(t)) \frac{\partial T}{\partial y} = \frac{1}{Pr} \frac{\partial^2 T}{\partial y^2} - Q_0 T + Q_1 C, \tag{9}$$

$$\phi \frac{\partial C}{\partial t} - (1 + \mathcal{E}f(t)) \frac{\partial C}{\partial y} = \frac{\phi}{Sc} \frac{\partial^2 C}{\partial y^2} - K_1 C. \tag{10}$$

With the following applicable conditions at the boundary

$$\begin{aligned}
u &= u_n, \quad T = 1, \quad C = 1, \quad \text{at } y = 0, \\
u &\rightarrow u(t), \quad T \rightarrow 0, \quad C \rightarrow 0, \quad \text{as } y \rightarrow \infty.
\end{aligned} \tag{11}$$

3. METHODOLOGY

To bring down the system of partial differential equations 8 – 10 to a system of ordinary differential equations in the non-dimensionless form using perturbation method, we assume the following for velocity, temperature, and concentration distribution of the flow field as the amplitude ($\varepsilon \ll 1$) of the permeability variation is very small.

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$$\left. \begin{aligned} u(y, t) &= u_o(y) + \varepsilon f(t)u_1(y) + 0(\varepsilon^2), \\ T(y, t) &= T_o(y) + \varepsilon f(t)T_1(y) + 0(\varepsilon^2), \\ C(y, t) &= C_o(y) + \varepsilon f(t)C_1(y) + 0(\varepsilon^2). \end{aligned} \right\} \quad (12)$$

where

$$\left. \begin{aligned} u(t) &= 1 + \varepsilon f(t), \\ f(t) &= e^{i\omega t}. \end{aligned} \right\} \quad (13)$$

Substituting equation 12 in equations 8 – 10, we get

Zero order of $\varepsilon, [0(\varepsilon^0)]$

$$u_o'' - u_o' - N_1 u_o = -(GrT_o + GmC_o), \quad (14)$$

$$T_o'' + PrT_o' - PrQ_o T_o = -PrQ_1 C_o, \quad (15)$$

$$C_o'' + \frac{Sc}{\phi} C_o' - \frac{Sc}{\phi} K_1 C_o = 0. \quad (16)$$

First order of $\varepsilon, [0(\varepsilon)]$;

$$u_1'' + u_1' - N_2 u_1 = -u_o' - GrT_1 - GmC_1, \quad (17)$$

$$T_1'' + PrT_1' - PrN_3 T_1 = -PrT_o' - PrQ_1 C_1, \quad (18)$$

$$C_1'' + \frac{Sc}{\phi} C_1' - \frac{Sc}{\phi} N_4 C_1 = -\frac{Sc}{\phi} C_o'. \quad (19)$$

Subject to the conditions at the boundary

$$\left. \begin{aligned} u_0 &= u_n, \quad u_1 = 0, \quad T_0 = 1, \quad T_1 = 0, \quad C_0 = 1, \quad C_1 = 0, \quad \text{at } y = 0, \\ u_0 &= 1, \quad u_1 = 1, \quad T_0 \rightarrow 0, \quad T_1 \rightarrow 0, \quad C_0 \rightarrow 0, \quad C_1 \rightarrow 0, \quad \text{as } y \rightarrow \infty. \end{aligned} \right\} \quad (20)$$

4. SOLUTION OF THE PROBLEM

Solving the differential equations from 14 – 19, using boundary conditions 20 and finally with the help of equations 12 and 13, we obtain the velocity, temperature, and concentration as follows

$$u(y, t) = R_6 \ell^{\alpha_5 y} + R_8 \ell^{\alpha_3 y} + R_9 \ell^{\alpha_1 y} + R_{10} \ell^{\alpha_1 y} + \varepsilon \ell^{\omega t} (R_{20} \ell^{\alpha_1 y} + R_{22} \ell^{\alpha_5 y} + R_{23} \ell^{\alpha_3 y} + R_{24} \ell^{\alpha_1 y} + R_{25} \ell^{\alpha_1 y} + R_{26} \ell^{\alpha_9 y} + R_{27} \ell^{\alpha_3 y} + R_{28} \ell^{\alpha_1 y} + R_{29} \ell^{\alpha_7 y} + R_{30} \ell^{\alpha_1 y} + R_{31} \ell^{\alpha_7 y} + R_{32} \ell^{\alpha_1 y}). \quad (21)$$

$$T(y, t) = (1 - R_5) \ell^{\alpha_3 y} + R_5 \ell^{\alpha_1 y} + \varepsilon \ell^{\omega t} (R_{14} \ell^{\alpha_9 y} + R_{16} \ell^{\alpha_3 y} + R_{17} \ell^{\alpha_1 y} + R_{18} \ell^{\alpha_7 y} + R_{19} \ell^{\alpha_1 y}) \quad (22)$$

$$C(y, t) = \ell^{\alpha_1 y} + \varepsilon \ell^{\omega t} (R_{11} \ell^{\alpha_7 y} + R_{13} \ell^{\alpha_1 y}) \quad (23)$$

The Skin – friction, Nusselt number, and Sherwood number are important physical parameters for this type of boundary layer flow. These parameters can be defined and determined as follows

Skin – friction

Based on the velocity field, the skin – friction at the plate can be obtained, which in non-dimensional form and is given by

$$C_f = -R_6 \alpha_5 - R_8 \alpha_3 - R_9 \alpha_1 - R_{10} \alpha_1 + \varepsilon \ell^{\omega t} (-R_{20} \alpha_1 - R_{22} \alpha_5 - R_{23} \alpha_3 - R_{24} \alpha_1 - R_{25} \alpha_1 - R_{26} \alpha_9 - R_{27} \alpha_3 - R_{28} \alpha_1 - R_{29} \alpha_7 - R_{30} \alpha_1 - R_{31} \alpha_7 - R_{32} \alpha_1). \quad (24)$$

Nusselt number

Based on the temperature field, the rate of heat transfer coefficient can be obtained, which in the non – dimensional form, in terms of the Nusselt number and is given by

$$-\left(\frac{\partial T}{\partial y}\right)_{y=0} = -\alpha_3 (1 - R_5) - R_5 \alpha_1 + \varepsilon \ell^{\omega t} (-R_{14} \alpha_9 - R_{16} \alpha_3 - R_{17} \alpha_1 - R_{18} \alpha_7 - R_{19} \alpha_1). \quad (25)$$

Sherwood number

Based on the concentration field, the rate of mass can be obtained, which in the non-dimensional form, in terms of the Sherwood number and is given by

$$-\left(\frac{\partial C}{\partial y}\right)_{y=0} = -\alpha_1 + \varepsilon l^{\omega t} (-R_{11}\alpha_7 - R_{13}\alpha_1). \quad 26$$

5. RESULTS AND DISCUSSION

The chemically reacting flow of MHD fluid through a porous medium has been studied. Approximate solutions are obtained for velocity, temperature, and concentration profiles using perturbation technique. The effects of the flow parameters such as magnetic intensity (A), chemical reaction (K_1), permeability (K), schmidt number (Sc), and prandlt number (Pr) on velocity, temperature, concentration profiles, heat transfer coefficient, and mass transfer coefficient of the flow fields are discussed with the aids of graphs. In our study, we had that

$$N_1 = A + \frac{\phi}{k} + \frac{1}{k}, N_2 = i\omega + A + \frac{\phi}{k} + \frac{1}{k}, N_3 = i\omega + Q_0,$$

$$N_4 = i\omega\phi + K_1. \text{ According to [9], } Gr = 4; Gm = 2; Q_1 = 2; k = 2; Q_0 = 2,$$

$$k_1 = 0.2; t = 1; \omega = 0.1; Sc = 0.2; u_n = 0.5; A = 2; Pr = 0.7; \varepsilon = 0.2; \phi = 0.5.$$

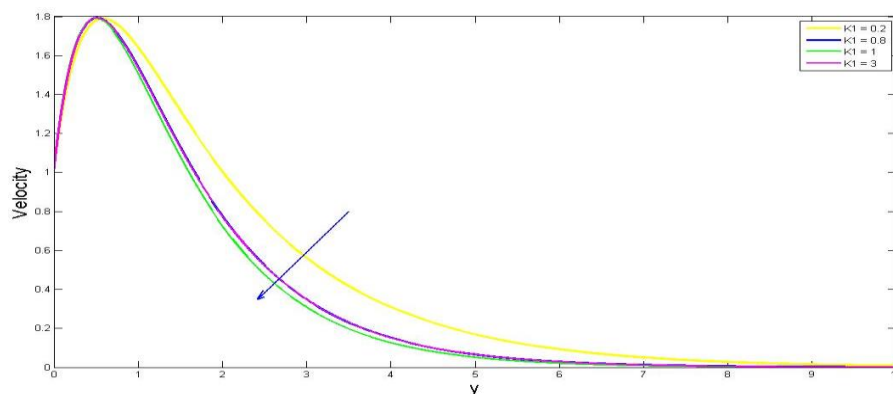


Figure 5.1: Effect of Chemical Reaction on Velocity Profile

Fig. 5.1 shows the impact of chemical reaction parameter on velocity profile. It is noticed that increasing K_1 from 0.2 to 0.8, 1 and to the highest value of 3, clearly decreases velocity at both the boundary layer region and the free stream region. This is because flow is retarded in the flow field as a result of drag and turbulent reaction.

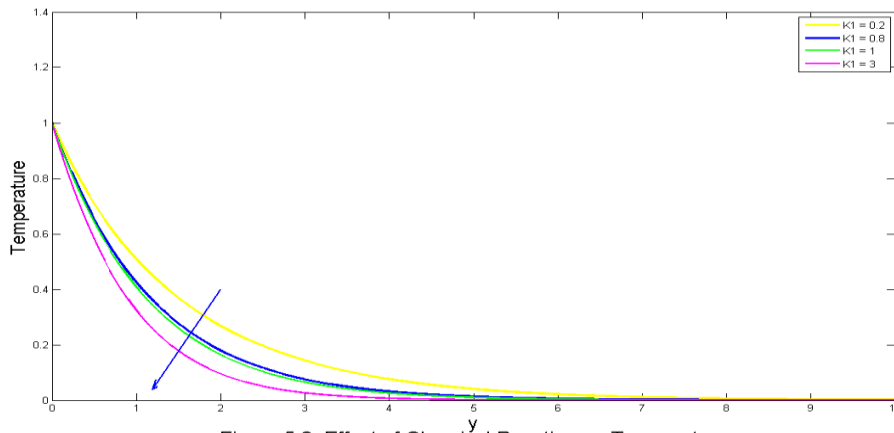


Figure 5.2: Effect of Chemical Reaction on Temperature

Fig. 5.2 displayed temperature profile for different values of chemical reaction parameter. It is seen that as chemical reaction parameter rises, the temperature profile decreases. This is because heat is not being released but rather utilized to facilitate the reaction (endothermic reaction).

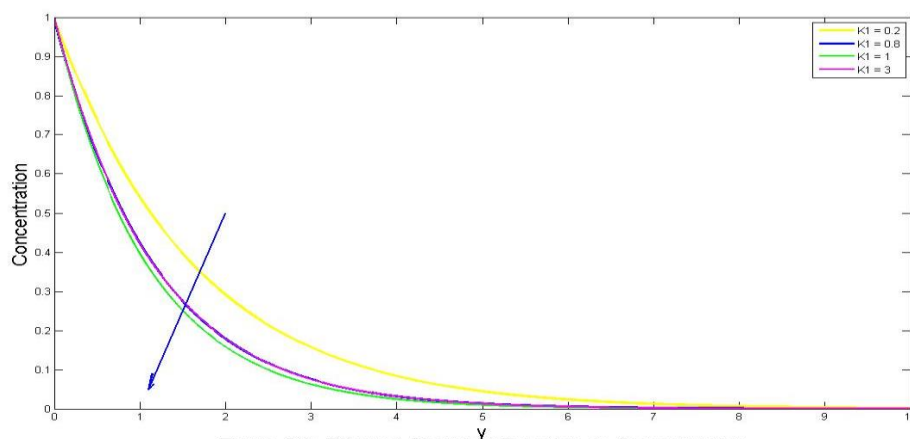


Figure 5.3: Effect of Chemical Reaction on Concentration

Fig. 5.3 shows the influence of chemical reaction parameter on concentration profile. It is observed that an increase in chemical reaction parameter results to decrease in concentration profile. It also

shows that, there is no effect of chemical reaction on concentration profiles at $k_1=3$, meaning that any increase in chemical reaction after $k_1=1$ shows no effect on concentration profiles. It shows that rate of chemical reaction cannot be increased unabated.

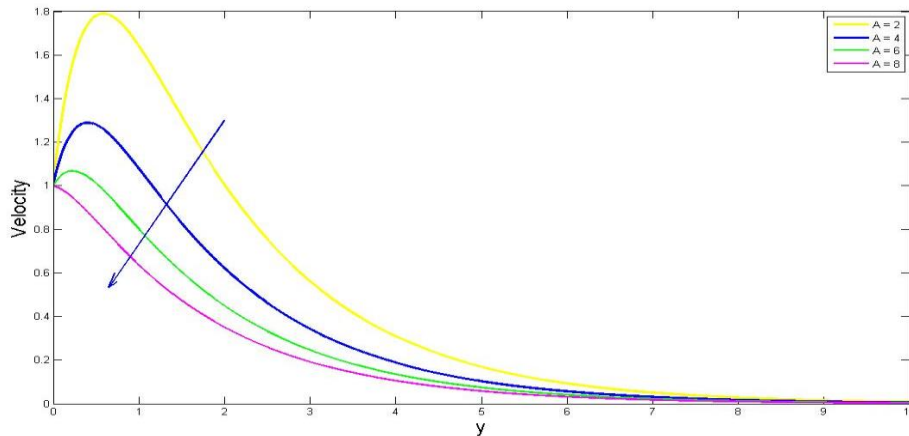


Figure 5.4: Effect of Magnetic field intensity on Velocity Profile

Fig. 5.4 shows the effect of magnetic intensity on velocity profile. It is seen that an increase in magnetic intensity decreases velocity. This is in line with the expectation, because the magnetic field exerts a retarding force on the free convection.

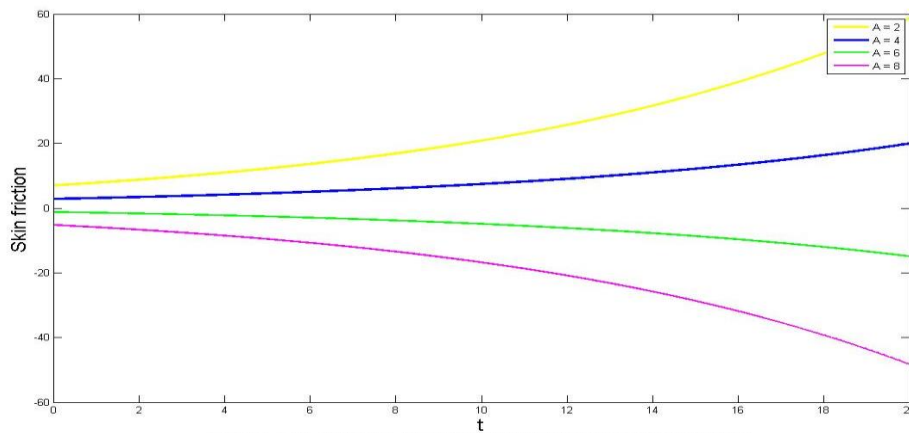


Figure 5.5: Effect of Magnetic field intensity on Skin friction

Fig. 5.5 illustrate the impact of magnetic field intensity on skin-friction coefficient. It shows that the increase in the values of magnetic intensity leads to decrease in skin-friction coefficient. As we can see from fig. 5.5, that the decrease is more at the stream region than at the boundary region.

This is because, at the free stream region, the skin-friction is mild (as a result of no flow competition) but at the boundary region, the skin-friction is high (as a result of porosity along the plate) thereby causing the skin-friction to reduce more at the stream region than at the boundary region.

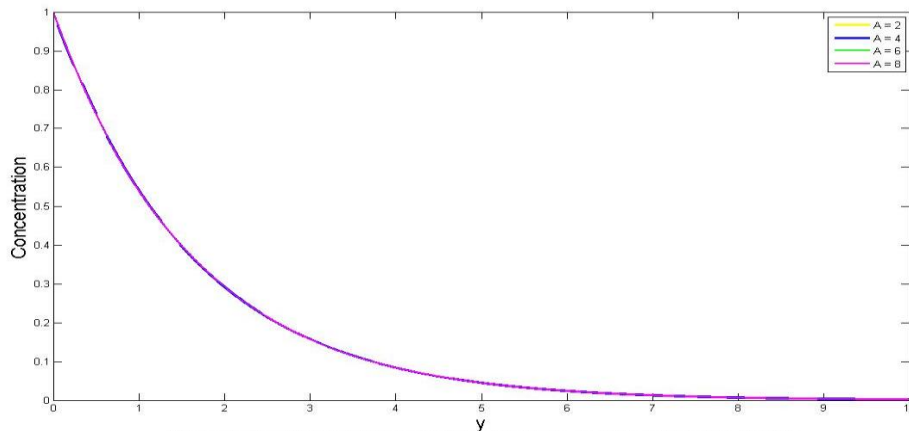


Figure 5.6: Effect of Magnetic field intensity on Concentration Profile

Fig 5.6 shows the effect of magnetic field intensity on concentration profile. It is observed that increasing magnetic intensity from 2 to 4, 6, and to the highest value of 8, shows no effect on concentration profile at both boundary and free stream region. This implies that increase in magnetic intensity does not bring any change on concentration profile at both boundary and stream region.

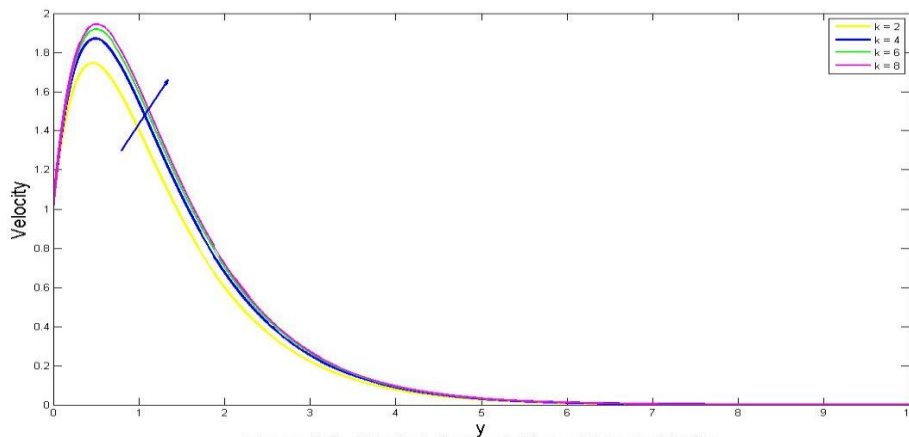


Figure 5.7: Effect of Permeability on Velocity Profile

Fig. 5.7 illustrates the influence of permeability on velocity profile. It can be seen that, velocity profile slowly increases as permeability increases. We also observed that at the free stream region, all velocity profiles are smoothly decayed to zero. This is because, at distant points from the plate (free stream region), nothing instigate velocity but at the boundary region, velocity is instigated by porosity and thereby causing velocity to rise close to the plate.

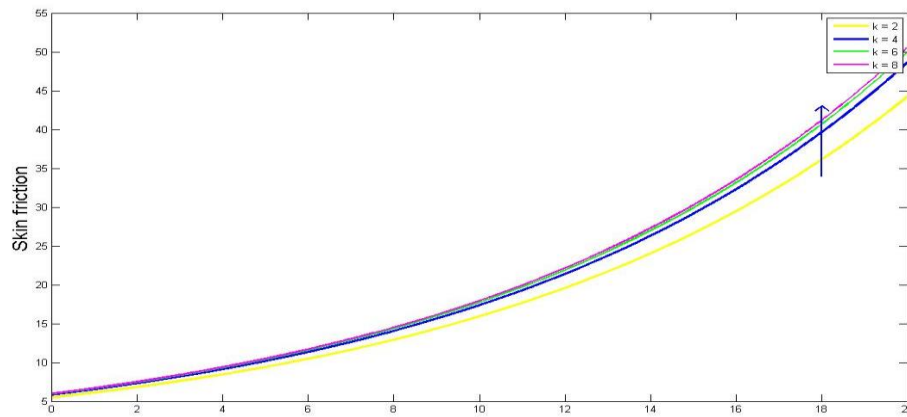


Figure 5.8: Effect of Permeability on Skin friction

Fig. 5.8 displayed the effect of permeability on skin-friction coefficient. It is seen that an increase in permeability from 2, 4, 6, and to the highest number of 8, results to increase on skin-friction coefficient. We also noticed that at a time in the increment of permeability, there will be no effect on skin-friction coefficient at both boundary and stream region. We as well observed that, the effect is more at the stream region than at the boundary region. This is because, at the boundary region, there is turbulence flow as a result of porosity along the plate, but far away from the plate (stream region), the flow is mild.

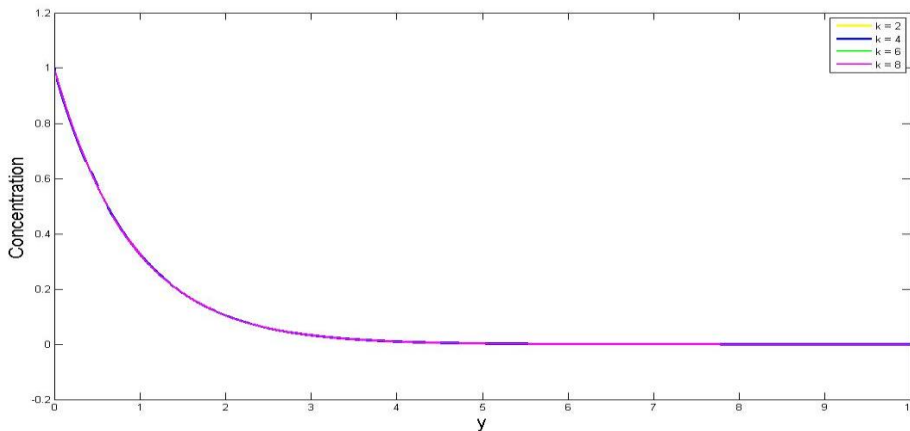


Figure 5.9: Effect of Permeability on Concentration Profile

Fig. 5.9 illustrates the effect of permeability on concentration profile. It is noticed that the increase in the values of permeability on concentration has no noticeable effect on concentration profile rather instigates concentration profile to be fully developed at a distant point from the plate (free stream region).

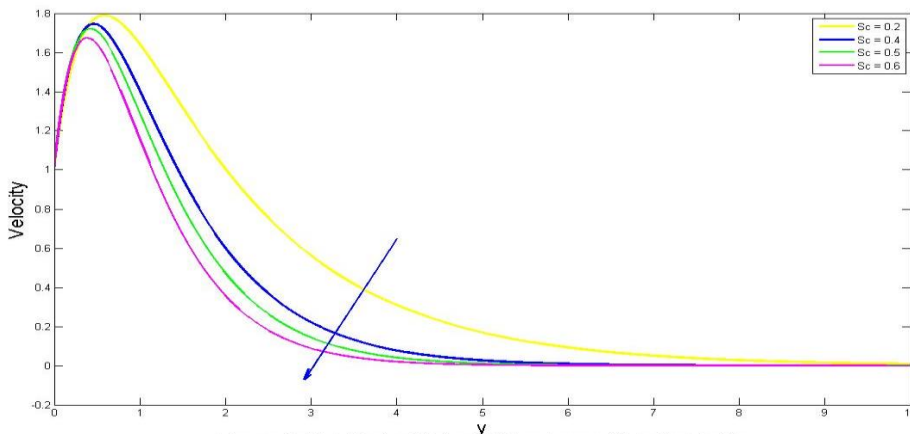


Figure 5.10: Effect of Schmidt Number on Velocity Profile

Fig. 5.10 displayed the effect of Schmidt number on velocity. It is seen that a rise in Schmidt number leads to decrease on velocity. We also observed that velocity is the same down the free stream region irrespective of the values of Schmidt number. This is as a result of no flow agitation at the free stream region.

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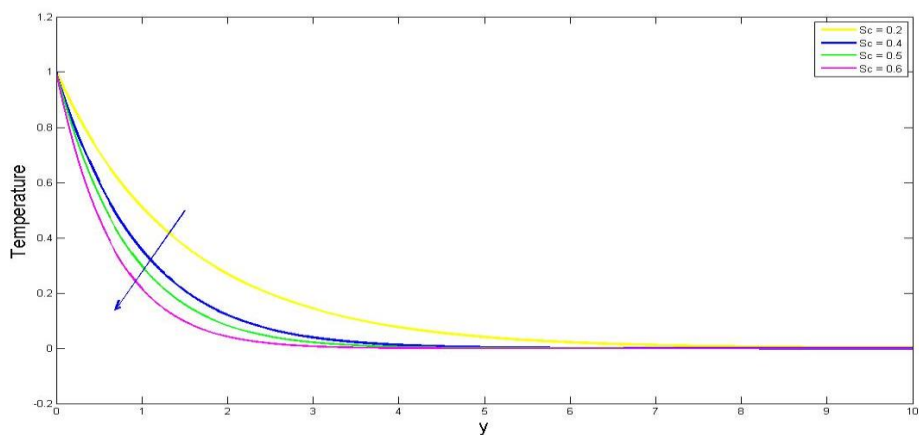


Figure 5.11: Effect of Schmidt number on Temperature

Fig. 5.11 illustrates the response of Schmidt number on temperature profile. It is observed that an increase in the values of Schmidt number from 0.2, 0.4 through 0.5 to 0.8 obviously resulted to decrease in temperature since heat is not released rather utilized to instigate the reaction. It is also noticed that temperature is the same at the stream region irrespective of the values assigned to Schmidt number.

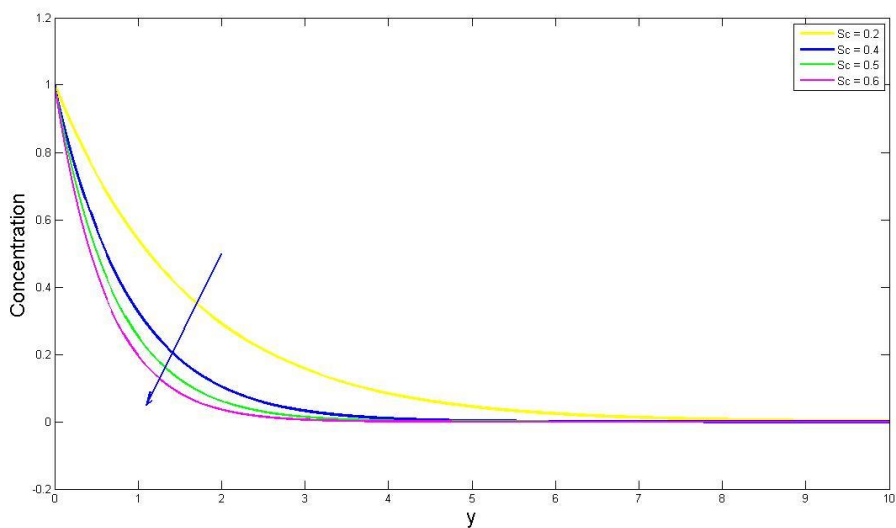


Figure 5.12: Effect of Schmidt Number on Concentration

Fig.5.12 displayed the effect of Schmidt number on concentration profile. It shows that increase in Schmidt number results to decrease on concentration profile. This is because the heavier the diffusing species the greater the retarding effect on concentration distribution of the flow field and as well the faster the flow become fully developed.

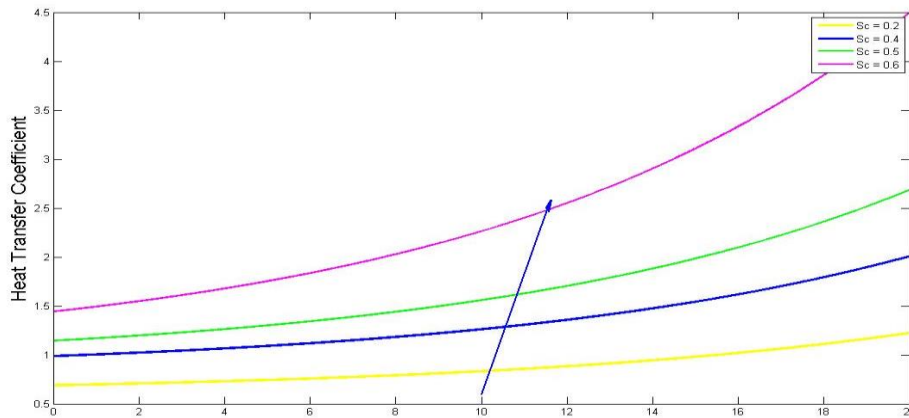


Figure 5.13: Effect of Schmidt Number on Heat Transfer Coefficient

Fig. 5.13 shows the effect of Schmidt number on heat transfer coefficient. It is seen that as Schmidt number increases the heat transfer coefficient also increases.

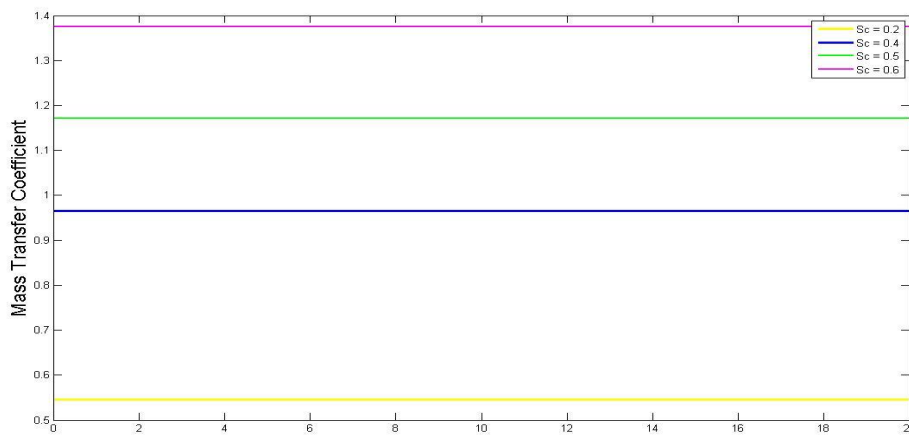


Figure 5.14: Effect of Schmidt Number on Mass Transfer Coefficient

Fig. 5.14 displayed the effect of Schmidt number on mass transfer coefficient. It is noticed that at each level of the Schmidt number, the mass transfer coefficient is the same at both boundary and stream region. However, variation of the Schmidt number varies the level of mass transfer

coefficient.

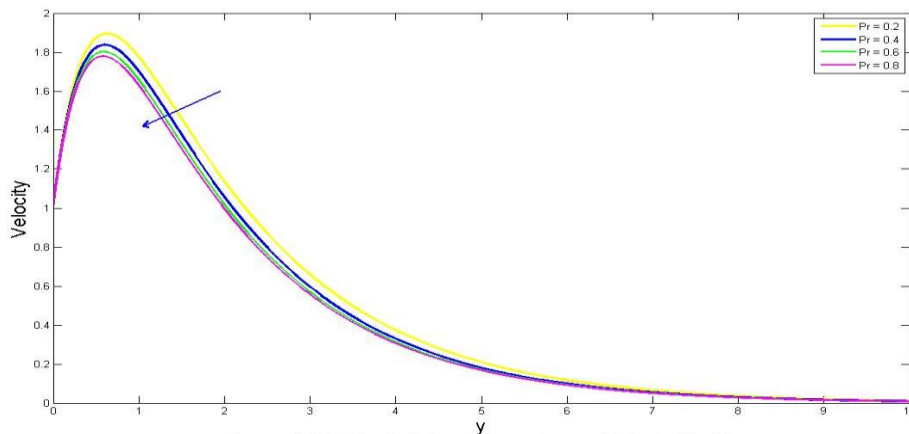


Figure 5.15: Effect of Prandtl number on Velocity Profile

Fig. 5.15 displayed the velocity profile for different values of Prandtl number. It is seen that increase in Prandtl number slowly reduces velocity. It is also noticed that continuous increase in Prandtl number shows no effect on velocity and that velocity decayed to zero level at the distant points from the plate (free stream region).

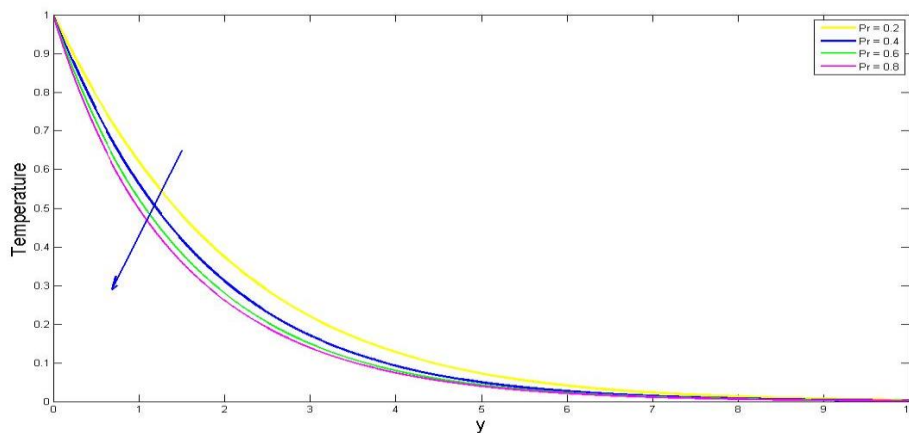


Figure 5.16: Effect of Prandtl number on Temperature

Fig. 5.16 showcases the effect of temperature for different values of Prandtl number. It is shown that increase in Prandtl number leads to decrease of the thermal boundary layer thickness and as such reduces the average temperature within the boundary layer. This is because, increasing values of Prandtl number equivalent to increase the thermal conductivities and as such heat is able to drop

from the heated plate more rapidly. Hence, in the case of smaller Prandtl numbers as the thermal boundary layer is thicker and therefore the rate of heat transfer depressed. We also observed that at distant points from the plate (stream region), temperature is at the zero level.

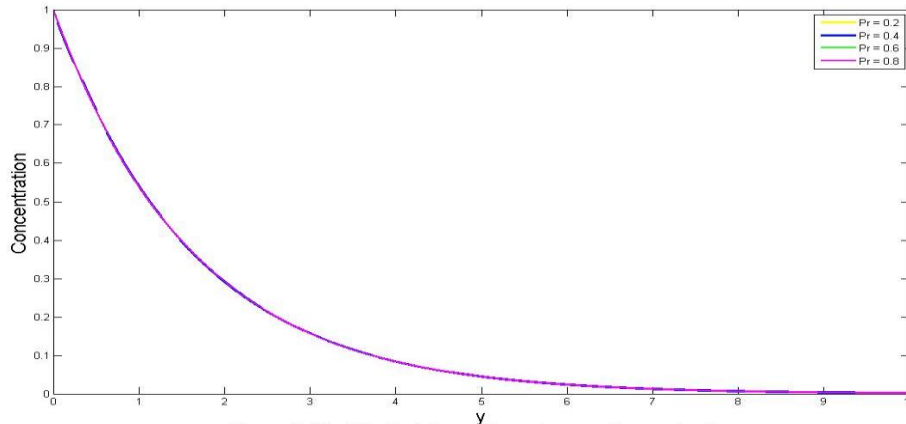


Figure 5.17: Effect of Prandtl number on Concentration

Fig. 5.17 shows the effect of prandtl number on concentration profile. It is observed that increase in prandtl number has no effect on concentration profile at both the boundary layer region and at the free stream region irrespective of the values of Prandti number.

Conclusion

The results of the physical interest on velocity, temperature, concentration, skin-friction, heat transfer, and mass transfer for the flow field are summarized herein as follow:

1. A growing magnetic intensity results to decrease in velocity, and skin-friction of the flow field at every point.
2. An increase in chemical reaction and Schmidt number leads to decrease on velocity at all point of the flow field.
3. Velocity and temperature decrease on increase of Prandtl number.
4. A growing chemical reaction and Schmidt number leads to decrease in temperature and concentration at every point of the flow field.
5. An increase in Prandtl number, Magnetic intensity, and Permeability shows no effect on concentration profile at every point of the flow field.

6. A growing Schmidt number increases both heat and mass transfer coefficient at every point of the flow field.
7. An increase in permeability increases skin-friction of the flow field at certain points.

APPENDIX

$$\alpha_1 = \frac{-\left(\frac{Sc}{\phi} + \sqrt{\left(\frac{Sc}{\phi}\right)^2 + 4K_1 \frac{Sc}{\phi}}\right)}{2}, \quad \alpha_2 = \frac{-\frac{Sc}{\phi} + \sqrt{\left(\frac{Sc}{\phi}\right)^2 + 4K_1 \frac{Sc}{\phi}}}{2}$$

$$\alpha_3 = \frac{-\left(\text{Pr} + \sqrt{(\text{Pr})^2 + 4\text{Pr}Q_o}\right)}{2}, \quad \alpha_4 = \frac{-\text{Pr} + \sqrt{(\text{Pr})^2 + 4\text{Pr}Q_o}}{2}$$

$$\alpha_5 = \frac{-(1 + \sqrt{1 + 4N_1})}{2}, \quad \alpha_6 = \frac{-1 + \sqrt{1 + 4N_1}}{2}$$

$$\alpha_7 = \frac{-\left(\frac{Sc}{\phi} + \sqrt{\left(\frac{sc}{\phi}\right)^2 + 4\frac{Sc}{\phi}N_4}\right)}{2}, \quad \alpha_8 = \frac{-\frac{Sc}{\phi} + \sqrt{\left(\frac{sc}{\phi}\right)^2 + 4\frac{Sc}{\phi}N_4}}{2}$$

$$\alpha_9 = \frac{-\left(\text{Pr} + \sqrt{(\text{Pr})^2 + 4\text{Pr}N_3}\right)}{2}, \quad \alpha_{10} = \frac{-\text{Pr} + \sqrt{(\text{Pr})^2 + 4\text{Pr}N_3}}{2}$$

$$\alpha_{11} = \frac{-(1 + \sqrt{1 + 4N_2})}{2}, \quad \alpha_{12} = \frac{-1 + \sqrt{1 + 4N_2}}{2}$$

$$R_3 = 1 - R_5, \quad R_5 = \frac{-\text{Pr}Q_1}{\alpha_1^2 + \text{Pr}\alpha_1 - \text{Pr}Q_o}, \quad R_6 = u_n - \ell^{-\infty} - R_8 - R_9 - R_{10}, \quad R_8 = \frac{-Gr(1 - R_5)}{\alpha_3^2 + \alpha_3 - N_1},$$

$$R_9 = \frac{-GrR_5}{\alpha_1^2 + \alpha_1 - N_1}, R_{10} = \frac{-Gm}{\alpha_1^2 + \alpha_1 - N_1}, R_{11} = \frac{Sc\alpha_1}{\alpha_1^2\phi + Sc\alpha_1 - ScN_4}, R_{13} = -\frac{Sc\alpha_1}{\alpha_1^2\phi + Sc\alpha_1 - ScN_4}$$

$$R_{14} = -(R_{16} + R_{17} + R_{18} + R_{19}), R_{16} = \frac{(1-R_5)Pr\alpha_3}{\alpha_3^2 + Pr\alpha_3 - PrN_3}, R_{17} = \frac{-R_5 Pr\alpha_1}{\alpha_1^2 + Pr\alpha_1 - PrN_3}$$

$$R_{18} = \frac{-R_{11} Pr Q_1}{\alpha_7^2 + Pr\alpha_7 - PrN_3}, R_{19} = \frac{-R_{13} Pr Q_1}{\alpha_1^2 + Pr\alpha_1 - PrN_3}, R_{20} = -(\ell^{-\infty} + R_{22} + R_{23} + R_{24} + \dots + R_{32})$$

$$R_{22} = \frac{-R_6\alpha_5}{\alpha_5^2 + \alpha_5 - N_2}, R_{23} = \frac{-R_8\alpha_3}{\alpha_3^2 + \alpha_3 - N_2}, R_{24} = \frac{-R_9\alpha_1}{\alpha_1^2 + \alpha_1 - N_2}, R_{25} = \frac{-R_{10}\alpha_1}{\alpha_1^2 + \alpha_1 - N_2},$$

$$R_{26} = \frac{-R_{14}Gr}{\alpha_9^2 + \alpha_9 - N_2}, R_{27} = \frac{-R_{16}Gr}{\alpha_3^2 + \alpha_3 - N_2}, R_{28} = \frac{-R_{17}Gr}{\alpha_1^2 + \alpha_1 - N_2}, R_{29} = \frac{-R_{18}Gr}{\alpha_7^2 + \alpha_7 - N_2},$$

$$R_{30} = \frac{-R_{19}Gr}{\alpha_1^2 + \alpha_1 - N_2}, R_{31} = \frac{-R_{11}Gm}{\alpha_7^2 + \alpha_7 - N_2}, R_{32} = \frac{-R_{13}Gm}{\alpha_1^2 + \alpha_1 - N_2}, u_n = R_6 + \ell^{-\infty} + R_8 + R_9 + R_{10}$$

CONFLICT OF INTERESTS

The author(s) declare that there is no conflict of interests.

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