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Effect of chemical reaction with heat and mass transfer over an inclined plate

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Abstract

An inclined channel is used to study the flow of an unsteady MHD free convection fluid under mass transfer and heat transfer with chemical reaction. In order to obtain the expression for velocity, temperature and concentration, the highly nonlinear coupled ordinary differential equations of the flow were transformed into ordinary differential equations. The expression for velocity, temperature and concentration is obtained using regular perturbation parameters. We show the effects of various parameters on velocity, temperature, and concentration, including Schmidt number, thermal Grashof number, singular Grashof number, chemical reaction, and angle of inclination.

Subject Classification: *70K60, 76D05, 80A99.*

Keywords: *Heat and mass transfer, MHD, Inclined plane.*

1. Introduction

Magnetohydrodynamics (MHD) studies how electrically conducting fluids move in magnetic field. A combination of liquid metals (like mercury and molten iron) and ionized gases is included in these fluids, including the solar atmosphere. The MHD principle is best illustrated by dynamos and motors. Various research studies have been conducted on the flow dynamics of unsteady MHD free convection in horizontal channels. In order to explore such flows,

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scientifically motivated applications were developed. In addition to magnetic drug targeting, MHD pumps are used for liquid metal cooling, power generation, and power generation by magnetic fields.

MHD research has been significantly influenced by a number of scholars and authors. It was investigated by Chamkha [1] that laminar flow is possible when two viscous, incompressible, electrically-conductive fluids with heat-producing or heat-absorbing properties are mixed. The study involved filling a uniform porous medium with a parallel-plate channel that was infinitely long and impermeable. To investigate simultaneous heat and mass transfer, Ganesan and Palani [2] investigated transient natural convection flows adjacent to an inclined plate. Further comparisons were conducted using the implicit Crank-Nicolson finite difference method. The phenomenon of longitudinal vortices was examined by Sparrow and Husar [3]. Additionally, they examined the characteristics of secondary convection flow overlaying natural convection on an inclined plate.

According to Angel et al. [4], free convection adjacent to an inclined flat plate can combine heat and mass transfer. A study conducted by Malashetty et al. [5] investigated the dynamics of two fluids flowing through an inclined channel equipped with porous and fluid layers. Shit and Haldar [6] studied magnetohydrodynamic (MHD) flow over a permeable stretching sheet with an incline. While discussing convection and heat transfer in an immiscible fluid, Daniel [7] spoke of an inclined channel undergoing a pressure gradient.

For the movement of immiscible fluids within porous channels, Punnam Chandar Bitla and Fekadu Yemataw Sitotaw [8] examined an inclined magnetic field and slip conditions. According to Hasan Nihal Zaidi and Naseem Ahmad [9], the study examined magnetohydrodynamic (MHD) convection flow that occurs between two immiscible fluids in an inclined channel that generates or absorbs thermal energy. A study by Sneha and Yadav [10] examined the movement of immiscible fluids inside porous channels, such as couple stress fluids and Jeffrey fluids.

Malashetty and Umavathi [11] examined two-phase magnetohydrodynamic discharges in inclined channels. According to Agarwal and Kumar [12], pulsating magnetohydrodynamic (MHD) flow occurs in an incompressible viscous porous media bounded by horizontal plates of two immiscible fluids, one conducting and the other non-conducting. Ramana Murthy and Srinivas [13] studied the flow of two immiscible liquids in an inclined porous medium with slip boundaries and magnetic fields. It was also necessary to use the Stokes model to define these couple stress fluids. As described by Beckermann et al. [14], a fluid-saturated porous medium was partially filled with a fluid-saturated layer of fluid flow and heat transfer.

According to Mankinde and Mhone [15], transverse magnetic fields interact with radiative heat transfer in a saturated porous medium in which an optically thin fluid flows unevenly through a channel with non-uniform temperature distributions on its walls. In a study by Gbadeyan and Dada [16], variable viscosity stretching sheets were investigated in laminar boundary layers for their interactions with radiation and Hall currents.

These previous studies led to an analysis of the effects of magnetohydrodynamics on free convection heat and mass transfer over inclined plates in the present study.

2. Problem formulation

If an incompressible viscous fluid flows over an inclined wall at an acute angle Φ , the flow should be steady and laminar. A constant temperature equal to ambient temperature T is maintained along with the desired mass flux. In this case, there is an x-axis flow, with the y-axis perpendicular to it and aligned with the semi-infinite inclined porous plane. It is evident from this analysis that the magnetic field has negligible influence over the applied magnetic field. Furthermore, we assume that all fluid properties remain constant. Based on Boussinesq's approximation and boundary layer assumptions, we can express the equations for mass, momentum, energy, and concentration as follows:

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

$$\rho\left(\frac{\partial U'}{\partial t'} + V'\frac{\partial U'}{\partial y'}\right) = \mu\frac{\partial^2 U'}{\partial y'^2} - \frac{\partial P'}{\partial x'} - \sigma B_0^2 U' + \rho g \beta_f (T - T'_w)\cos\Phi + \rho g \beta_c^* (C - C'_w)\cos\Phi \tag{2}$$

$$\rho C_p\left(\frac{\partial T'}{\partial t'} + V'\frac{\partial T'}{\partial y'}\right) = k\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y} \tag{3}$$

$$\frac{\partial C'}{\partial t'} + V'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} - K_1(C - C'_w) \tag{4}$$

The fluid's boundary conditions are as follows:

$$t \le 0 : \; u' = 0, T' = T'_w, C' = C'_w \text{ for all } y$$

$$t' > 0 : \begin{cases} u' = U_0, T' = T'_w + (T - T_w)At', \\ C' = C'_w + (C - C_w)AT' \; at \; y = 0, \\ u' = 0, T' \to T'_w, C' \to C'_w \; as \; y \to \infty \end{cases} \tag{5}$$

We can write (1) and (4) as a function of time only, because V' is independent of y'. Hence, we can write [(1) and (4) as a function of time only].

$$V' = V_0(1 + \varepsilon A e^{i\omega t}) \tag{6}$$

Assuming that $V'_1 = V'$. ε this quantity is so small that it has a positive value. $\varepsilon A \ll 1$. A non-zero constant mean velocity V_0 is assumed here to be the transpiration velocity V'. Dimensionless quantities can be calculated as follows:

$$U = \frac{U'}{u}, y = \frac{y'}{h}, t = \frac{t'v}{h^2}, V = \frac{h}{v_1}V' = \frac{V}{V_0}, P = \frac{-h^2}{\mu u}\left(\frac{\partial P'}{\partial x'}\right), \theta = \frac{T' - T'_\infty}{T'_W - T'_\infty}, Pr = \frac{\mu c_p}{k},$$

$$K^2 = \frac{h^2}{K'}, Sc = \frac{v}{D}, C = \frac{C' - C'_\infty}{C'_W - C'_\infty}, M^2 = \frac{\sigma h^2 B_0^2}{\mu}, F = \frac{4I'h^2}{k}, \frac{\partial q_r}{\partial y} = 4(T'_w - T'_\infty)I',$$

$$Gc = \frac{\rho g h^2 \beta_c^*(C'_W - C'_\infty)}{\mu u}, Gr = \frac{\rho g h^2 \beta_f (T'_W - T'_\infty)}{\mu u}, Kc = \frac{vK_l}{v_w^2}.$$

Equation (2), (3), (4) becomes

$$\frac{\partial U}{\partial t}+(1+\varepsilon e^{i\omega t})\frac{\partial U}{\partial y}=\frac{\partial^2 U}{\partial y^2}+P-M^2U+Gr\theta\cos\Phi+GcC\cos\Phi \tag{7}$$

$$\frac{\partial\theta}{\partial t}+(1+\varepsilon e^{i\omega t})\frac{\partial\theta}{\partial y}=\frac{1}{Pr}\frac{\partial^2\theta}{\partial y^2}-\frac{F\theta}{Pr} \tag{8}$$

$$\frac{\partial C}{\partial t}+(1+\varepsilon e^{i\omega t})\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-\frac{Kc}{Sc}C_1 \tag{9}$$

The boundary conditions in dimensionless form are given as follows:

$$\left.\begin{array}{l} u=1,\theta=t,C=c, at\ y=0 \\ u=0,\theta=0,C=0, at\ y\to\infty \end{array}\right\} \tag{10}$$

3. Method to Solve

Under the governing equations (7-9), solving the boundary conditions (10) requires expanding $U_1(y,t)$, $\theta_1(y,t)$, $C_1(y,t)$, as a power series perturbative parameter ε.

$$U(y,t)=U_{10}(y)+\varepsilon e^{i\omega t}U_{11}(y)$$
$$\theta(y,t)=\theta_{10}(y)+\varepsilon e^{i\omega t}\theta_{11}(y)$$
$$C(y,t)=C_{10}(y)+\varepsilon e^{i\omega t}C_{11}(y)$$

Using equations (7) to (9), we substitute periodic and non-periodic terms, neglecting those containing ε^2, these ordinary differential equations result from the above procedure.

Non-Periodic Terms:

$$\frac{\partial^2 U_{10}}{\partial y^2}-\frac{\partial U_{10}}{\partial y}-M^2U_{10}=-P-Gr\theta_{10}\cos\Phi-GcC_{10}\cos\Phi \tag{11}$$

$$\frac{\partial^2\theta_{10}}{\partial y^2}-Pr\frac{\partial\theta_{10}}{\partial y}-F\theta_{10}=0 \tag{12}$$

$$\frac{\partial^2 C_{10}}{\partial y^2}-Sc\frac{\partial C_{10}}{\partial y}-K_C C_{10}=0 \tag{13}$$

Periodic terms:

$$\frac{\partial^2 U_{11}}{\partial y^2}-\frac{\partial U_{11}}{\partial y}-(M^2+i\omega)U_{11}=\frac{\partial U_{10}}{\partial y}-Gr\theta_{11}\cos\Phi-GcC_{11}\cos\Phi \tag{14}$$

$$\frac{\partial^2\theta_{11}}{\partial y^2}-Pr\frac{\partial\theta_{11}}{\partial y}-(F+i\omega Pr)\theta_{11}=Pr\frac{\partial\theta_{10}}{\partial y} \tag{15}$$

$$\frac{\partial^2 C_{11}}{\partial y^2}-Sc\frac{\partial C_{11}}{\partial y}-(i\omega S_c+K_C)C_{11}=Sc\frac{\partial C_{10}}{\partial y} \tag{16}$$

Despite the fact that the coefficients are constant, equations (11) and (16) can be considered to be ordinary linear coupled differential equations. As a result, boundary conditions become,

$$\left.\begin{array}{c} U_{10}=1\,, U_{11}=0, \theta_{10}=te^{-\omega t}, \theta_{11}=0, C_{10}=te^{-\omega t}, C_{11}=0 \\ at\ y=0 \\ U_{10}=0\,, U_{11}=0, \theta_{10}=0, \theta_{11}=0, C_{10}=0, C_{11}=0 \\ at\ y\to\infty \end{array}\right\} \tag{17}$$

According to the boundary conditions (17), the solutions of (11) -(16) as follows:

$$U_{10}(y)=C_5e^{m_5y}+C_6e^{m_6y}+K_1+K_2e^{m_1y}+K_3e^{m_2y}+K_4e^{m_3y}+K_5e^{m_4y} \tag{18}$$

$$\theta_{10}(y)=C_1e^{m_1y}+C_2e^{m_2y} \tag{19}$$

$$C_{10}(y)=C_3e^{m_3y}+C_4e^{m_4y} \tag{20}$$

$$U_{11}(y)=C_{11}e^{m_{11}y}+C_{12}e^{m_{12}y}+K_{10}e^{m_1y}+K_{11}e^{m_2y}+K_{12}e^{m_3y}+K_{13}e^{m_4y}+K_{14}e^{m_5y}+K_{15}e^{m_6y}+K_{16}e^{m_7y}+K_{17}e^{m_8y}+K_{18}e^{m_9y} \tag{21}$$

$$\theta_{11}(y)=C_7e^{m_7y}+C_8e^{m_8y}+K_6e^{m_1y}+K_7e^{m_2y} \tag{22}$$

$$C_{11}(y)=C_9e^{m_9y}+C_{10}e^{m_{10}y}+K_8e^{m_3y}+K_9e^{m_4y} \tag{23}$$

Where,

$V_1=F+i\omega Pr$, $V_2=i\omega Sc$, $V_3=M^2+i\omega$, $m_1=\frac{Pr+\sqrt{Pr^2+4F}}{2}$, $m_2=\frac{Pr-\sqrt{Pr^2+4F}}{2}$, $m_3=\frac{Sc+\sqrt{Sc^2+4K_c}}{2}$, $m_4=\frac{Sc-\sqrt{Sc^2+4K_c}}{2}$, $m_5=\frac{1+\sqrt{1+4M^2}}{2}$, $m_6=\frac{1-\sqrt{1+4M^2}}{2}$, $m_7=\frac{Pr+\sqrt{Pr^2+4V_1}}{2}$, $m_8=\frac{Pr-\sqrt{Pr^2+4V_1}}{2}$, $m_9=\frac{Sc+\sqrt{Sc^2+4V_2}}{2}$, $m_{10}=\frac{Sc-\sqrt{Sc^2+4V_3}}{2}$, $m_{11}=\frac{1+\sqrt{1+4V_3}}{2}$ $m_{12}=\frac{1-\sqrt{1+4V_3}}{2}$ $r_1=e^{-m_2}$, $r_2=1-e^{(m_1-m_2)}$, $r_3=e^{-m_4}$, $r_4=1-e^{(m_3-m_4)}$, $r_5=m_4e^{-m_4}$, $r_6=m_4e^{(m_3-m_4)}-m_3$, $r_7=m_2e^{-m_2}$, $r_8=m_1e^{(m_1-m_2)}-m_1$, $r_9=m_6e^{(m_5-m_6)}-m_5$, $r_{10}=m_{12}e^{(m_{11}-m_{12})}-m_{11}$, $r_{11}=m_8e^{(m_7-m_8)}-m_7$, $r_{12}=m_{10}e^{(m_9-m_{10})}-m_9$, $r_9=1-e^{(m_9-m_{10})}$, $r_{10}=m_{11}-m_{12}e^{(m_{11}-m_{12})}$, $K_1=\frac{P}{M^2}$, $K_2=-\frac{GcC_1\cos\Phi}{m_1^2-m_1-M^2}$, $K_3=-\frac{GrC_2\cos\Phi}{m_2^2-m_2-M^2}$, $K_4=-\frac{GcC_3\cos\Phi}{m_3^2-m_3-M^2}$, $K_5=-\frac{GcC_4\cos\Phi}{m_4^2-m_4-M^2}$, $K_6=\frac{PrC_1m_1}{m_1^2-Prm_1-V_1}$, $K_7=\frac{PrC_2m_2}{m_2^2-Prm_2-V_1}$, $K_8=\frac{ScC_3m_3}{m_3^2-Scm_3-V_2}$, $K_9=\frac{ScC_4m_4}{m_4^2-Scm_4-V_2}$, $K_{10}=\frac{K_2m_1-GcK_6}{m_1^2-m_1-V_3}$, $K_{11}=\frac{K_3m_2-GrK_7}{m_2^2-m_2-V_3}$, $K_{12}=\frac{K_4m_3-GcK_8}{m_3^2-m_3-V_3}$, $K_{13}=\frac{K_5m_4-GcK_9}{m_4^2-m_4-V_3}$, $K_{14}=\frac{C_5m_5}{m_5^2-m_5-V_3}$, $K_{14}=\frac{C_5m_5}{m_5^2-m_5-V_3}$, $K_{15}=\frac{C_6m_6}{m_6^2-m_6-V_3}$, $K_{16}=\frac{N_1C_7}{m_7^2-m_7-V_3}$, $K_{17}=\frac{N_1C_8}{m_8^2-m_8-V_3}$, $K_{18}=\frac{N_2C_9}{m_9^2-m_9-V_3}$, $K_{19}=\frac{N_2C_{10}}{m_{10}^2-m_{10}-V_3}$,

$N_1=-Gr\cos\Phi$, $N_2=-Gc\cos\Phi$, $A_6=1-(K_6e^{m_1}+K_7e^{m_2})$,

$A_1=K_2m_1e^{m_1}+K_3m_2e^{m_2}+K_4m_3e^{m_3}+K_5m_4e^{m_4}$,

$A_2=K_1+K_2e^{m_1}+K_3e^{m_2}+K_4e^{m_3}+K_5e^{m_4}$,

$A_3=K_2m_1+K_3m_2+K_4m_3+K_5m_4$, $A_8=1-(K_8e^{m_3}+K_9e^{m_4})$,

$A_4=K_{10}e^{m_1}+K_{11}e^{m_2}+K_{12}e^{m_3}+K_{13}e^{m_4}+K_{14}e^{m_5}+K_{15}e^{m_6}+K_{16}e^{m_7}+K_{17}e^{m_8}+K_{18}e^{m_9}+K_{19}e^{m_{10}}$,

$A_5 = K_{10}m_1 + K_{11}m_2 + K_{12}m_3 + K_{13}m_4 + K_{14}m_5 + K_{15}m_6 + K_{16}m_7 + K_{17}m_8 + K_{18}m_9 + K_{19}m_{10}$, $A_7 = K_6m_1 + K_7m_2$, $A_9 = K_8m_3 + K_9m_4$, $Q_1 = A_3 - A_2m_6e^{-m_6}$, $Q_2 = A_5 - A_4m_{12}e^{-m_{12}}$, $Q_3 = A_7 + A_6m_8e^{-m_8}$, $Q_4 = A_9 + A_8m_{10}e^{-m_{10}}$, $C_1 = \frac{r_7}{r_8}$, $C_2 = e^{-m_2} - C_1e^{(m_1-m_2)}$, $C_3 = \frac{r_5}{r_6}$, $C_4 = e^{-m_4} - C_3e^{(m_3-m_4)}$, $C_5 = \frac{Q_1}{r_9}$, $C_6 = -A_2e^{-m_6} - C_5e^{(m_5-m_6)}$, $C_7 = \frac{Q_3}{r_{11}}$, $C_8 = A_6e^{-m_8} - C_7e^{(m_7-m_8)}$, $C_9 = \frac{Q_4}{r_{12}}$, $C_{10} = A_8e^{-m_{10}} - C_9e^{(m_9-m_{10})}$, $C_{11} = \frac{Q_2}{r_{10}}$, $C_{12} = -A_1e^{-m_{12}} - C_{11}e^{(m_{11}-m_{12})}$.

4. Results and discussion

We investigate the velocity, temperature, and concentration profiles of an incompressible viscous electrically conducting fluid in the presence of a semi-infinite inclined wall.

Based on Figures 1 and 2, different velocity profiles can be seen for different thermal and solutal Grashof numbers. A thermal Grashof number Gr, measures thermal buoyancy forces in boundary layers. We observe an increase in velocity because of the thermal buoyancy force. Additionally, with higher Gr values, peak velocity increases rapidly within the porous region. As such, the Grashof number (Gc), which governs the relationship between buoyancy and viscous hydrodynamic force, plays an important role. In species with increasing buoyancy forces, fluid velocity increases, and its peak value becomes more distinct. Toward the plate, the velocity distribution peaks before gradually decreasing to the free stream value. This velocity shows a direct correlation with an increase in solutal Grashof number.

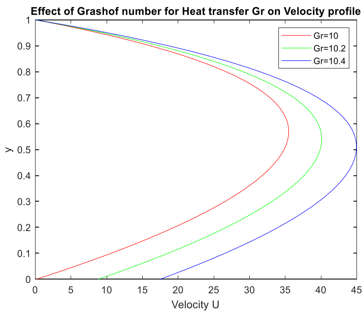

Figure 1
Velocity profile impact of Gr.

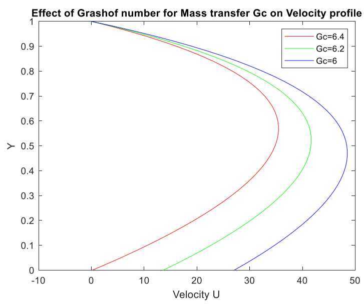

Figure 2
Velocity profile impact of Gc.

In Figure 3, we can see how surface inclination impacts velocity. As the angle of inclination (Φ) increases, velocity decreases. In vertical motion, the plate's speed reaches its maximum. The fluid velocity on a vertical surface is greater than that on an inclined surface. As a result of gravity (g cos(Φ),) buoyancy effects are reduced on inclined plates, resulting in the difference. In addition, velocity varies depending on inclination.

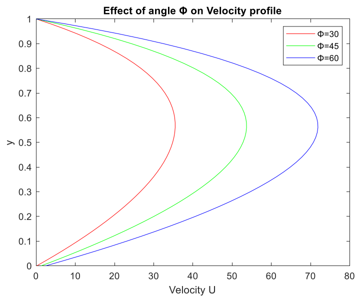

Figure 3
Velocity profile impact of angle *Φ*.

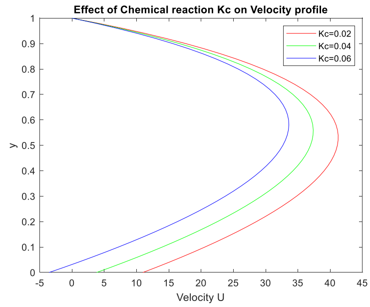

Figure 4
Effect of Kc in Velocity profile.

Figures 4 and 5 show how chemical reactions affect velocity and concentration. Fluid velocity and concentration decrease as chemical reaction increases. The case is based on homogeneous first-order chemical reactions. It is clear from this that chemical reaction parameters have a tremendous impact on diffusion rates.

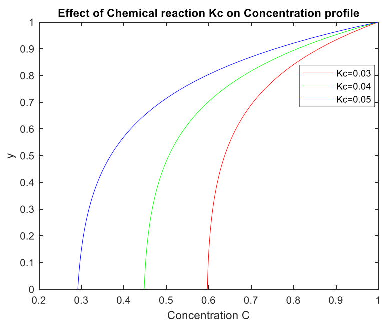

Figure 5
Concentration impact of Kc.

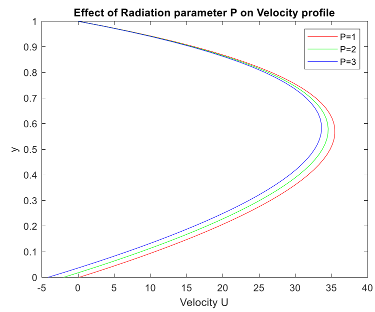

Figure 6
Velocity profile impact of P.

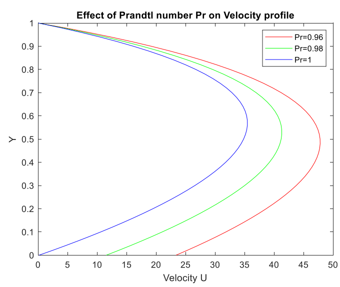

Figure 7
Velocity profile impact of Pr.

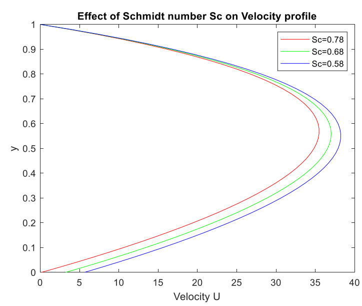

Figure 8
Velocity profile impact of Sc.

Based on various values of the pressure gradient, Figure 6 shows how it affects the velocity profile. In Figure 7, the Prandtl number is shown to have an impact on the velocity field. Even with an increase in the Prandtl number, the velocity of the flow diminishes as momentum diffusivity progressively surpasses thermal diffusivity.

In Figure 8, the electromagnetic force gradually gains dominance over the viscous force. A velocity and concentration profile is illustrated in Figure 8 and 9 based on the Schmidt number (Sc). As Sc increases, the concentration decreases. According to the buoyancy force, this behaviour is the result of buoyancy. Both the momentum and concentration boundary layers decrease in thickness due to the concurrent decrease in velocity and concentration profiles. As Sc decreases, the molecular diffusivity (D) reduces, thereby shrinking the concentration boundary layer. Consequently, higher Sc values lead to a greater number of species, while lower Sc values result in fewer species.

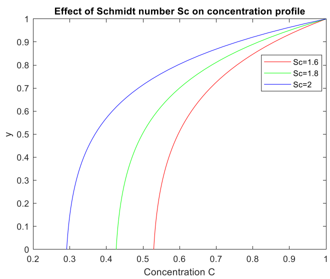

Figure 9
Concentration impact of Sc.

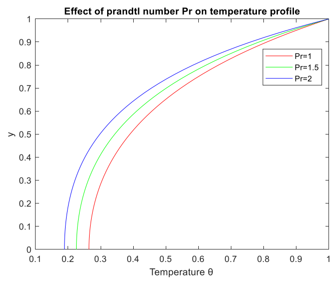

Figure 10
Temperature impact of Pr.

An increase in Prandtl number (Pr) correlates with a reduction in temperature distribution in Figure 10. Figures 10 and 11 show temperature profiles related to Prandtl numbers (Pr) and radiation parameters (F). This phenomenon occurs because the thermal boundary layer becomes thinner with an increase in Pr. The temperature profiles in Figure 11 show a slight decrease when the thermal conductivity ratios increase with radiation parameter values.

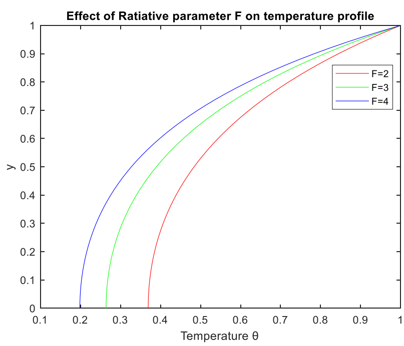

Figure 11
Temperature impact of F.

5. Conclusion

It has been studied the unsteady free convection of fluids in an inclined channel with heat and mass transfer. By using dimensionless parameters, the governing equations, which are momentum, energy, and species concentration equations are written in dimensionless form. It was determined that the distributions of velocity, temperature, and concentration were evaluated and solved by using a perturbation method. This concludes that both the heat Grashof number and mass Grashof number indicate an increase in fluid velocity, while the viscosity ratio indicates a decrease. Prandtl number, thermal conductivity ratio, and radiation parameter increase with an increase in temperature and concentration, respectively. Through the use of free convection in an inclined channel with immiscible fluid flows, this study will provide a better understanding of flow, heat transfer, and mass transfer.

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