Chapter - IV

MASS TRANSFER EFFECTS ON MHD MIXED CONVECTIVE PERIODIC FLOW THROUGH POROUS MEDIUM IN AN INCLINED CHANNEL WITH TRANSPIRATION COOLING AND THERMAL RADIATION

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CHAPTER IV

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4.1. INTRODUCTION

Transpiration cooling can very effectively protect certain structural elements in turbojet and rocket engines, like combustion chamber walls, exhaust nozzles or gas turbine blades from hot gases. Eckert and Drake [8] and Jain and Bansal [13] described the reduction of heat transfer in couette flow for the case of an incompressible fluid by injecting the fluid into the flow field from the stationary plate and corresponding removable of heat from the moving plate. The problem is two dimensional due to the uniform injection and suction applied at the porous plates. Flow and heat transfer along a plane wall with periodic suction velocity was studied by Gersten and Gross [10]. Effects of such a suction velocity on various flow and heat transfer problems along horizontal and vertical plates also studied extensively by Singh et al. [22], Ahmed and Sharma [1], Chaudhary and Chand [7], Singh and Sharma [20] and Gehlot and Tak [9]. However, the transverse sinusoidal injection or suction velocity in the problem of transpiration cooling has not attracted much attention. Singh [21] studied three dimensional Couette flow with transpiration cooling. In geothermal region a situation may arise when slip of particles at the boundary may occur. Keeping this in mind, Gupta and Goyal [11], Jothimani and Anjali Devi [15], Jain and Taneja [14] and others have solved their problems by considering first order velocity slip conditions (Street [23]).

The magneto fluid dynamics is the study of electrically conducting fluids in electric and magnetic fields. It unifies in a common framework the electromagnetic and fluid dynamic theories to yield a description of the concurrent effects of magnetic field on the flow and the flow on the magnetic field. Magneto hydrodynamics (MHD) is specifically concerned with electrically conducting liquids and ionized compressible gases. Alpher [3] investigated the heat transfer in magneto hydrodynamic flow between parallel plates. Magneto hydrodynamic flow between
two parallel plates with heat transfer was investigated by Attia and Kotb [5]. Singh and Mathew [18] investigated the effects of injection/suction on an oscillatory hydro magnetic flow in a rotating horizontal channel. Exact solution of an oscillatory free convective MHD flow in a rotating channel in the presence of radiative heat has also been studied by Singh and Garg [17]. Singh [19] analyzed an oscillatory flow of electrically conducting fluid with heat radiation in a horizontal porous channel.

Umemure and Law [24] developed a generalized formulation for the natural convection boundary layer flow over a flat plate with arbitrary inclination. They found that the flow characteristics depend not only on the extent of inclination but also on the distance from the leading edge. Hossain et al [12] studied the free convection flow form an isothermal plate inclined at a small angle to the horizontal. Anghel at al [4] presented a numerical solution of free convection flow past an inclined surface. Chen [6] performed an analysis to study the natural convection flow over a permeable inclined surface with variable wall temperature and concentration. They observed that increasing the angle of inclination decreases the effect of buoyancy force. Alam et al [2] investigated heat and mass transfer effects on MHD free convective fluid flow past an inclined plate with heat generation. Rajesh kumar at al. [16] presented a numerical solution of transient MHD free convection flow of dusty viscous fluid along an inclined plate with ohmic dissipation.

In view of these, we studied the effects of heat and mass transfer on unsteady periodic flow of a viscous incompressible and electrically conducting fluid in a horizontal channel. The lower stationary plate and the upper plate in an unsteady periodic motion are subjected to a same constant injection and suction velocity respectively. The temperature of the upper plate in periodic motion varies periodically with time. The flow in the channel also acted upon by periodic variation of pressure gradient. A closed form solution of the problem is obtained. The effects of various flow parameters on the velocity, temperature and concentration fields have been discussed with the aid of graphs.

4.2. FORMULATION OF PROBLEM

We considered the unsteady periodic flow of a viscous incompressible and electrically conducting fluid through porous medium in an inclined channel with horizontal. The two insulated plates of the channel are distance 'd' apart. The fluid is
injected through the lower stationary porous plate and sucked through the upper porous plate in oscillating motion in its own plane. The constant injection and the suction velocities at both the porous plates is \( V \). A Cartesian coordinate system \((X^*, Y^*)\) is introduced the \( X^*\)-axis lies along the centerline of the channel and \( Y^*\)-axis along the magnetic field of uniform strength \( B_s \) is applied, is perpendicular to the parallel plates. The Reynolds number is assumed to be very small so that the induced magnetic field is negligible. The temperature difference of the plates is assumed to be high enough to induce radiation heat. The concentration difference of the plates is assumed to be high enough to induce radiation mass. All the physical quantities are independent of \( X^* \) for this problem of fully developed laminar flow.

In this analysis following assumptions are made.

i. The flow is unsteady and laminar.

ii. A magnetic field of uniform strength is applied normal to the flow.

iii. The magnetic Reynolds number is assumed to be very small so that the induced magnetic field is negligible.

iv. Hall current polarization and electrical effects are neglected.

v. Thermal and concentration buoyancy effects are considered.

vi. It is assumed that the fluid is optically thin with relatively slow density.

vii. The radiative heat flux in the \( x^* \)-direction is negligible.

viii. Mass transfer effects are assumed.

The flow is then governed by the following equations:

\[
\frac{\partial \rho^*}{\partial \gamma} = 0 \tag{4.2.1}
\]

\[
\frac{\partial u^*}{\partial t^*} + \nu \frac{\partial u^*}{\partial \gamma^*} = -\frac{1}{\rho} \frac{\partial p^*}{\partial \gamma^*} + \nu \frac{\partial^2 u^*}{\partial \gamma^*^2} - \frac{\sigma B^2_{s} u^*}{\rho} - \frac{\nu}{K^*} u^* + g \beta T^* \sin \alpha + g \beta \gamma^* \sin \alpha \tag{4.2.2}
\]
\[
\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{k}{\rho c_p} \frac{\partial^2 T^*}{\partial y^*^2} - \frac{1}{\rho c_p} \frac{\partial p^*}{\partial y^*}
\]  \hspace{1cm} (4.2.3)

\[
\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D \frac{\partial^2 C^*}{\partial y^*^2}
\]  \hspace{1cm} (4.2.4)

Where \( u^* (y^*, t^*) \) is the axial velocity, \( t^* \) is the time, \( p^* \) is the pressure, \( \rho \) is the fluid density, \( \nu \) is the kinematic viscosity, \( \sigma \) is the electric conductivity, \( k \) is the thermal conductivity, \( c_p \) is the specific heat at constant pressure. It is assumed that the fluid is optically thin with relatively low density and the radiative heat flux is given by

\[
\frac{\partial q^*}{\partial y^*} = 4\alpha^2 T^*
\]  \hspace{1cm} (4.2.5)

Where \( \alpha \) is the mean radiation absorption coefficient.

The boundary conditions relevant to the problem are

\( y^* = -d/2 : u^* = 0, v^* = \nu, T^* = 0, C^* = 0 \) \hspace{1cm} (4.2.6)

\( y^* = d/2 : u^* = U \cos \omega^* t^*, v^* = \nu, T^* = T_0 \cos \omega^* t^*, C^* = C_0 \cos \omega^* t^* \) \hspace{1cm} (4.2.7)

Where \( \omega^* \) is the frequency of oscillations. For the oscillatory internal flow in the channel the periodic pressure gradient variations are assumed to be of the form

\[
-\frac{1}{\rho} \frac{\partial p^*}{\partial x^*} = P \cos \omega^* t^*
\]  \hspace{1cm} (4.2.8)

Because the problem of assumption of constant injection and suction velocity \( V \) at the upper and lower plates respectively, continuity equation (4.1) integrates to

\( v^* = \nu \)  \hspace{1cm} (4.2.9)

Substituting equation (4.9) and introducing the following non-dimensional parameters into

\[
x = \frac{x^*}{d}, \eta = \frac{y^*}{d}, \frac{u}{U}, \frac{T}{T_0}, \frac{t}{\nu}, \frac{\omega}{\omega^*}, \frac{p}{\rho U V}, \frac{C}{C_0}, \frac{\nu}{D}
\]  \hspace{1cm} (4.2.10)
equations (4.2.2), (4.2.3) and (4.2.4), we get

\[
\frac{\omega}{\text{Re}} \frac{\partial u}{\partial \eta} + \frac{\partial u}{\partial \eta} = -\frac{\partial p}{\partial x} + \frac{1}{\text{Re}} \frac{\partial^2 u}{\partial \eta^2} - \frac{M^2}{K \text{Re}} u - \frac{1}{\text{KRe}} u + \frac{Gr}{\text{Re}} T \sin \alpha + \frac{Gm}{\text{Re}} C \sin \alpha \tag{4.2.11}
\]

\[
\frac{\omega}{\text{Re}} \frac{\partial T}{\partial \eta} + \frac{\partial T}{\partial \eta} = \frac{1}{\text{RePr}} \frac{\partial^2 T}{\partial \eta^2} - \frac{N^2}{\text{RePr}} T \tag{4.2.12}
\]

\[
\frac{\omega}{\text{Re}} \frac{\partial C}{\partial \eta} + \frac{\partial C}{\partial \eta} = \frac{1}{\text{ReSc}} \frac{\partial^2 C}{\partial \eta^2} \tag{4.2.13}
\]

Where

\[
\text{Re} = \frac{V d}{v}, \text{Pr} = \frac{\mu c_p}{k}, N = 2\alpha \frac{d}{\sqrt{k}}, K = \frac{K^*}{d}, Gr = \frac{g \beta d^2 T_0}{\nu v^3}, M = B \frac{d}{\sqrt{\mu}}
\]

\[
Gm = \frac{g \beta d^2 C_0}{\nu V}
\]

The boundary conditions in dimensionless form become

\[
u = 0, T = 0, C = 0, \text{at } \eta = -\frac{1}{2} \tag{4.2.14}
\]

\[
u = \cos t, T = \cos t, C = \cos t, \text{at } \eta = \frac{1}{2} \tag{4.2.15}
\]

### 4.3. SOLUTION OF THE PROBLEM

The mathematical solution of this periodic flow in the porous channel when the fluid is also acted upon by a periodic drop in pressure, we assume the solution in the complex notations as

\[
u(\eta,t) = u_0(\eta)e^{i\omega t}, T(\eta,t) = \theta_0(\eta)e^{i\omega t}, C(\eta,t) = \phi_0(\eta)e^{i\omega t}, -\frac{\partial p}{\partial x} = Pe^{i\omega t} \tag{4.3.1}
\]

Where \(P\) is a constant pressure. The real part of the solution will have physical significance.

The boundary conditions (4.2.14) and (4.2.15) can also be written in complex notations as
Substituting equation (4.3.1) into equations (4.2.11), (4.2.12) and (4.2.13), we get

\[ u_0 = \text{Re} u_0 - (i \omega + M^2 + K^{-1}) u_0 = -PRe - Gr \sin \alpha \theta_0 - Gm \sin \alpha \phi_0 \]  
\[ \theta_0' = \text{Re} Pr \theta_0 - (i \omega Pr + N^2) \theta_0 = 0 \]  
\[ \phi'_0 = \text{Re} Sc \phi_0 - (i \omega Sc) \phi_0 = 0 \]

These ordinary differential equations denote differentiation with respect to \( y \).

The boundary conditions (4.3.2) and (4.3.3) are reduced to

\[ u_0 = 0, \theta_0 = 0, \phi_0 = 0 \text{ at } \eta = -\frac{1}{2} \]  
\[ u_0 = 1, \theta_0 = 1, \phi_0 = 1 \text{ at } \eta = \frac{1}{2} \]

The solutions of equations (4.3.4), (4.3.5) and (4.3.6) under the boundary conditions (4.3.7) and (4.3.8) are obtained as

\[ u(\eta, t) = \left[ \begin{array}{c} \text{Gr} \sin \alpha \frac{1}{2} \text{sinh} \left( \frac{\eta}{2} \right) \left( c_1 (e^{\frac{m-1}{2}} - e^{-\frac{m-1}{2}}) + c_2 (e^{\frac{m+1}{2}} - e^{-\frac{m+1}{2}}) \right) \\ + \frac{Gm \sin \alpha}{2 \text{sinh} \left( \frac{P-q}{2} \right)} \left( c_3 (e^{m+1} - e^{-m+1}) + c_4 (e^{m-1} - e^{-m-1}) \right) \end{array} \right] \]

\[ \frac{\text{Gr} \sin \alpha}{2 \text{sinh} \left( \frac{r-s}{2} \right)} \left( e^{\frac{m+1}{2}} - e^{-\frac{m+1}{2}} \right) - \frac{Gm \sin \alpha}{2 \text{sinh} \left( \frac{P-q}{2} \right)} \left( e^{\frac{m-1}{2}} - e^{-\frac{m-1}{2}} \right) e^b \]

(4.3.9)
From the velocity field obtained in equation (4.3.9), we can find skin-friction \( \tau \) at the lower plate as

\[
\tau = |F| \cos(\tau + \phi)
\]

For \( F = F_1 + iF_2 = \frac{1}{2 \sinh \left( \frac{m-n}{2} \right)} \left( \begin{array}{c}
\frac{2 \sinh \left( \frac{n}{2} \right)}{2 \sinh \left( \frac{m-n}{2} \right)} + \frac{Gr \sin \alpha}{2 \sinh \left( \frac{r-s}{2} \right)} ((c_1(m-n)e^{-\frac{m}{2}}) + c_1(m-n)e^{-\frac{n}{2}})
\end{array} \right) + \frac{Gr \sin \alpha}{2 \sinh \left( \frac{r-s}{2} \right)} ((c_1(m-n)e^{-\frac{m}{2}}) + c_1(m-n)e^{-\frac{n}{2}})
\]

\[
\left( \begin{array}{c}
\frac{-Gr \sin \alpha}{2 \sinh \left( \frac{r-s}{2} \right)} c_1 e^{-\frac{r-s}{2}} \frac{-RePr}{2} \frac{Gm \sin \alpha}{2 \sinh \left( \frac{r-s}{2} \right)} c_1 e^{-\frac{r-s}{2}} \frac{-ReSc}{2}
\end{array} \right)
\]

The amplitude \(|F|\) and the phase angle \( \phi \) of the skin-friction can be calculated with the help of the following expressions

\[
|F| = \sqrt{F_1^2 + F_2^2}, \quad \phi = \tan^{-1} \frac{F_2}{F_1}
\]

From the temperature field obtained in equation (4.3.10), we can find Nusselt-number \( Nu \) at the lower plate as

\[
Nu = |f| \cos(\tau + \psi)
\]
The amplitude $|H|$ and the phase angle $\psi$ of the Nusselt number can be calculated with the help of the following expressions

$$|H| = \sqrt{H_r^2 + H_i^2}, \psi = \tan^{-1}\frac{H_i}{H_r}$$

(4.3.17)

From the concentration field obtained in equation (4.3.11), we can find Sherwood number $\bar{S}h$ at the lower plate as

$$\bar{S}h = |G| \cos(t + \theta)$$

(4.3.18)

$$G = G_r + iG_i = \frac{(p - q)e^{\frac{-i\pi}{2}}}{2 \sinh \left( \frac{p - q}{2} \right)}$$

(4.3.19)

The amplitude $|G|$ and the phase angle $\theta$ of the Sherwood number can be calculated with the help of the following expressions

$$|G| = \sqrt{G_r^2 + G_i^2}, \theta = \tan^{-1}\frac{G_i}{G_r}$$

(4.3.20)

4.4. RESULTS AND DISCUSSION

In order to study the effects of various physical parameters like porous permeability $K$, Grashof number $Gr$, modified Grashof number $G_m$ and influence of acute angle parameter appearing in the flow problem, we have carried out numerical calculations for the velocity, temperature, concentration, amplitudes of skin friction, phase angle of skin friction, amplitude of the Nusselt number, phase angle of the Nusselt number, amplitude of the Sherwood number and phase angle of the Sherwood number. The results obtained show that the dimensionless velocity is affected by physical parameters such as permeability parameter $K$, Grashof number $Gr$, modified Grashof number $G_m$ and influence of acute angle parameter $\alpha$ and magnetic field parameter $M$ respectively.
values of acute angle $\alpha$ to the horizontal. From this figure it is observed that the increase of acute angle $\alpha$ leads to the increase of amplitude of the skin friction $|F|$.

Comparing the numerical solution of K.D. Singh[19] from Figure 4.10 represents amplitude of the skin friction $|F|$ for various values of Hartmann number M. It is found that the amplitude of the skin friction $|F|$ decreases with an increase in Hartmann number M in the absence of Grashof number (Gr), modified Grashof number (Gm), porous permeability parameter (K), inclined angle ($\alpha$) and mass transfer. The agreement between these results is excellent.

The phase angle of the skin friction for various parameters against $\alpha$ is illustrated from figures 4.11 to 4.15. From Fig. 4.11 shows the variations of the phase angle of the skin friction $\phi$ with different values of porous permeability parameter (K). It is observed that the phase angle of the skin friction $\phi$ decreases with an increase in permeability parameter (K). Figure 4.12 illustrates the influences of Grashof number Gr on the phase angle of the skin friction $\phi$. It is observed that the phase angle of the skin friction $\phi$ decreases with an increase in Grashof number Gr. Figure 4.13 displays the effects of modified Grashof number on the phase angle of the skin friction $\phi$. It is observed that phase angle of the skin friction $\phi$ decreases with an increase in mass Grashof number Gm. Figure 4.14 reveals the effects of acute angle $\alpha$ to the horizontal, on the phase angle of the skin friction $\phi$. From this figure it is found that the phase angle of the skin friction $\phi$ decreases with an increase in acute angle $\alpha$ to the horizontal.

Comparing the numerical solution of K.D. Singh[19] in Figure 4.15 represents the effects of Hartmann number M on the phase angle of the skin friction $\phi$. It is seen that phase angle of the skin friction $\phi$ increases with an increase in Hartmann number M in the absence of Grashof number (Gr), modified Grashof number (Gm), porous permeability parameter (K), inclined angle ($\alpha$) and mass transfer. The agreement between these results is excellent.

Figure 4.16 represents temperature profiles for different values of radiation parameter N. From this diagram it is seen that the temperature decreases with an increase in radiation parameter N. For different values of radiation parameter N, the amplitude of the Nusselt number $|H|$ profiles are plotted in figure 4.17. From this
it is found that the amplitude of the Nusselt number $|H|$ decreases with an increase in radiation parameter $N$. Figure 4.18 illustrates that the profiles of phase angle of Nusselt number $\psi$ profiles for different values of radiation parameter $N$. It is observed that phase angle of Nusselt number $\psi$ increases with an increase in radiation parameter $N$.

Figure 4.18 reveals the effects of Schmidt number $Sc$ on the concentration $C$. It is observed that the concentration $C$ decreases with an increase in Schmidt number $Sc$. The amplitude of Sherwood number $|G|$ is studied in figure 4.20. It is observed that the amplitude of the Sherwood number $|G|$ decreases with an increase in Schmidt number $Sc$. Figure 4.21 illustrates the influences of Schmidt number $Sc$ on the phase angle of the Sherwood number $\theta$. It is seen that phase angle of the Sherwood number $\theta$ decreases with an increase in Schmidt number $Sc$.

4.5. CONCLUSIONS

In this chapter, we analyzed the mass transfer effects on MHD mixed convective periodic flow through porous medium in an inclined channel with transpiration cooling and thermal radiation. The governing equations are solved analytically. The solutions for velocity, temperature and concentration fields are obtained in terms of exponential and complimentary functions. From this investigation, the following observations have been drawn.

1. Velocity decreases with increasing values of Hartmann number $M$ or acute angle $\alpha$ while it increases with increasing values of porous permeability or Grashof number or modified Grashof number.

2. Temperature decreases with increasing values of radiation parameter.

3. Concentration decreases with increasing values of Schmidt number.

4. Phase angle of the skin friction decreases with increasing values of porous permeability or Grashof number or modified Grashof number.

5. Phase angle of the Sherwood number oscillates between the phase lag and the phase lead for the values of Schmidt number as the frequency of the oscillation decreases.
Fig 4.1 Velocity profiles for different $K$ with $Pr = 0.7$, $\omega = 5$, $Sc = 0.6$, $Re = 1$, $N = 1$, $t = 0$, $\alpha = 45$, $P = 5$, $Gr = 1$, $M = 2$ and $Gm = 1$.

Fig 4.2 Velocity profiles for different $Gr$ with $K = 0.1$, $Pr = 0.7$, $\omega = 5$, $Sc = 0.6$, $Re = 1$, $N = 1$, $t = 0$, $\alpha = 45$, $P = 5$, $M = 2$ and $Gm = 1$. 

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Fig. 4.3 Velocity profiles for different $Gm$ with $K = 0.1, \text{Pr} = 0.7, \omega = 5, \text{Sc} = 0.6, \text{Re}=1, t = 0, \alpha = 45, P = 5, \text{Gr}=1$ and $M = 2$

Fig. 4.4 Velocity profiles for different $\alpha$ with $K = 0.1, \text{Pr} = 0.7, \omega = 5, \text{Sc} = 0.6, \text{Re}=1, N = 1, t = 0, M = 2, P = 5, \text{Gr}=1$ and $Gm=1$
Fig. 4.5 Velocity profiles for different $M$ with $K = 1000$, $Pr = 0$, $\omega = 5$, $Sc = 0$, $Re = 1$, $N = 0$, $t = 0$, $\alpha = 0$, $P = 5$, $Gr = 0$ and $Gm = 0$

Fig. 4.6 Amplitude of the Skin function for different $K$ with $Pr = 0.7$, $P = 5$, $Sc = 0.6$, $Re = 1$, $N = 1$, $M = 2$, $t = 0$, $\alpha = 45$, $Gr = 1$ and $Gm = 1$
Fig. 4.7 Amplitude of the Skin function for different $Gr$ with $Pr=0.7, P=5, Sc=0.6$, $Re=1, N=1, M=2, t=0, \alpha=45, K=0.1$ and $Gm=1$

Fig. 4.8 Amplitude of the Skin function for different $Gm$ with $Pr=0.7, P=5$, $Sc=0.6, Re=1, N=1, M=2, t=0, \alpha=45, K=0.1$ and $Gr=1$
Fig. 4.9 Amplitude of the Skin function for different $K$ with $Pr = 0.7$, $P = 5$, $Sc = 0.6$, $Re = 1$, $N = 1$, $M = 2$, $t = 0$, $\alpha = 45$, $Gr = 1$ and $Gm = 1$.

Fig. 4.10 Amplitude of the Skin function for different $M$ with $Pr = 0$, $P = 5$, $Sc = 0$, $Re = 0.5$, $N = 0$, $K = 1000$, $t = 0$, $\alpha = 0$, $Gr = 0$ and $Gm = 0$. 

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Fig. 4.11 Phase angle of the Skin function for different $K$ with $\alpha = 45$, $P = 5$, $Pr = 0.7$, $Sc = 0.6$, $Re = 1$, $N = 1$, $M = 2$, $t = 0$, $Gm = 1$ and $Gr = 1$

Fig. 4.12 Phase angle of the Skin function for different $Gr$ with $\alpha = 45$, $P = 5$, $Pr = 0.7$, $Sc = 0.6$, $Re = 1$, $N = 1$, $M = 2$, $t = 0$, $Gm = 1$ and $K = 0.1$
Fig. 4.13 Phase angle of the Skin function for different $Gm$ with $\alpha = 45, P = 5, Pr = 0.7, Sc = 0.6, Re = 1, N = 1, M = 2, t = 0, Gr = 1$ and $K = 0.1$

Fig. 4.14 Phase angle of the Skin function for different $\alpha$ with $Gr = 1, P = 5, Pr = 0.7, Sc = 0.6, Re = 1, N = 1, M = 2, t = 0, Gm = 1$ and $K = 0.1$
Fig. 4.15 Phase angle of the Skin function for different $M$ with $\alpha = 0$, $P = 5$, $Pr = 0$, $Sc = 0$, $Re = 0.5$, $N = 0$, $Gr = 0$, $t = 0$, $Gm = 0$ and $K = 1000$

Fig. 4.16 Temperature profiles for different $N$ with $t = 0$, $\omega = 5$, $Pr = 0.7$ and $Re = 1$. 

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Fig. 4.17 Amplitude of the Nusselt number for different $N$ with $t = 0, Pr = 0.7$ and $Re = 1.7$.

Fig. 4.18 Phase angle of Nusselt number for different $N$ with $t = 0, Re = 1$ and $Pr = 0.7$. 

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Fig. 4.19 Concentration profiles for different $Sc$ with $t = 0, Re = 1$ and $\omega = 5$

Fig. 4.20 Amplitude of the Sherwood number for different $Sc$ with $t = 0$ and $Re = 1$. 

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Fig. 4.21 Phase angle of the Sherwood number for different $Sc$ with $t = 0$ and $Re = 1$. 

$Sc = 0.01, 0.6, 0.78$
REFERENCES


APPENDIX

\[ c = \frac{P\Re}{i\omega + M^2 + K^{-1}} \]

\[ m = \frac{\text{Re} + \sqrt{\text{Re}^2 + 4(i\omega + M^2 + K^{-1})}}{2} \]

\[ n = \frac{\text{Re} - \sqrt{\text{Re}^2 + 4(i\omega + M^2 + K^{-1})}}{2} \]

\[ r = \frac{\text{RePr} + \sqrt{\text{Re}^2 \text{Pr}^2 + 4(i\omega \text{Pr} + N^2)}}{2} \]

\[ s = \frac{\text{RePr} - \sqrt{\text{Re}^2 \text{Pr}^2 + 4(i\omega \text{Pr} + N^2)}}{2} \]

\[ p = \frac{\text{ReSc} + \sqrt{\text{Re}^2 \text{Sc}^2 + 4(i\omega \text{Sc})}}{2} \]

\[ q = \frac{\text{ReSc} - \sqrt{\text{Re}^2 \text{Sc}^2 + 4(i\omega \text{Sc})}}{2} \]

Where \( c_1 = r^2 - \text{Re} \left( r \left( i\omega + K^{-1} + M^2 \right) \right), c_2 = s^2 - \text{Re} \left( s \left( i\omega + K^{-1} + M^2 \right) \right), \)

\( c_3 = p^2 - \text{Re} \left( p \left( i\omega + K^{-1} + M^2 \right) \right), c_4 = q^2 - \text{Re} \left( q \left( i\omega + K^{-1} + M^2 \right) \right), \)

\[ c_2 = \frac{e^{\frac{1}{2}}}{c_1}, c_6 = e^{-\frac{1}{2}} \left( \frac{c_1 - c_2}{c_2} \right), c_1 = \frac{e^{\frac{1}{2}}}{c_3}, c_5 = e^{-\frac{1}{2}} \left( \frac{c_1 - c_2}{c_2 c_3} \right), c_4 = e^{-\frac{1}{2}} \left( \frac{c_1 - c_2}{c_3} \right), \]

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