CHAPTER 5
EFFECTS OF MASS TRANSFER AND HEAT FLUX ON CONVECTIVE FLOW PAST A MOVING VERTICAL CYLINDER WITH CHEMICAL REACTION

5.1 Introduction:
In most chemical reactions, the reaction rate depends on the concentration of the species itself. In many chemical engineering processes there is a chemical reaction between a foreign mass and a fluid. These processes take place in numerous industrial applications such as manufacturing of ceramics, food processing and polymer production. The effects of mass transfer on flow past an impulsively started infinite vertical plate under constant heat flux condition along with chemical reactions were studied by Das et al. [18]. The dimensionless governing equations were solved by the usual Laplace Transform method. Ganesan and Loganathan [42] studied free convection boundary layer flow of a viscous and incompressible fluid past an impulsively started semi-infinite vertical cylinder with uniform heat and mass fluxes and chemically reactive species. Numerical solutions were derived by the finite-difference scheme of Crank-Nicolson type. On diffusion of chemically reactive species in convective flow along a vertical cylinder has been investigated by Ganesan and Rani [37]. The authors discuss the Nusselt number, Sherwood number for both generative and destructive reaction. Muthucumaraswamy and Shankar [75] studied the first order chemical reaction on unsteady flow past a uniformly accelerated isothermal infinite vertical plate with heat and mass transfer in the presence of thermal radiation. The interaction of free convection with thermal radiation of a viscous incompressible unsteady flow past a moving vertical cylinder with heat and mass transfer is analyzed by Ganesan and Loganathan [43]. Muthucumaraswamy and Valliammal [74] studied the unsteady flow past an exponentially accelerated infinite vertical plate with variable temperature and uniform mass diffusion, in the presence of a homogeneous chemical reaction of first order. Transient free convection about vertical plates and circular cylinders was studied by Goldstein and Briggs [46]. They discussed the transient free convection, heat transfer problem from vertical flat plate and vertical circular cylinders to a surrounding initially quiescent fluid. Also the velocity field and penetration distance in integral form were given for a vertical circular cylinder surrounded by a fluid of arbitrary Prandtl number. Chambre and Young [13]
investigated a first order chemical reaction in the neighborhood of a flat plate. They discussed for both generative and destructive reaction. Bottemanne [8] studied the experimental results for a vertical cylinder with combined effects of heat and mass transfer for $Pr = 0.71$ and $Sc = 0.63$. Chen and Yuh [15] analyzed steady heat and mass transfer processes near cylinders with uniform wall heat and mass fluxes and wall temperature numerically. Das et al. [20] studied the mass transfer effect on moving isothermal vertical plate in the presence of chemical reaction. The dimensionless governing equations were solved by the usual Laplace transform technique. Mahapatra et al. [68] investigated the heat and mass transfer effect on a steady flow of viscous fluid through a porous medium bounded by a porous surface in the presence of homogeneous chemical reaction of first order. The non-linear MHD flow with heat and mass transfer of an incompressible, viscous and electrically conducting fluid on moving semi-infinite vertical cylinder in the presence of chemical reaction were discussed by Loganathan et al. [66]. They solved the governing boundary layer equations using an implicit finite difference scheme of Crank-Nicolson method.

But in nature, the presence of pure air or water is rather impossible. It is always possible that a foreign mass is either present naturally in air or water or foreign masses are mixed with air or water. We assume that a chemically reactive species is emitted from the surface of the cylinder and diffuses into the fluid. It is also assumed that reaction takes place entirely in the stream. Due to the importance in many applications in the field of science and technology, the present study is required. It is proposed to study convective flow past a moving vertical cylinder under the effects of heat flux and mass transfer along with first order chemical reaction. The solutions are obtained by Laplace Transform technique for the velocity, temperature and concentration fields and these are presented in graphs. Skin friction and Sherwood number are also obtained and illustrated graphically.

5.2 Mathematical Analysis:
Consider unsteady laminar and viscous flow past a moving semi-infinite vertical cylinder of radius $r_0$ with uniform heat flux and mass diffusion. Here the x-axis is taken along the axis of the cylinder in the vertically upward direction, and the radial coordinate $r$ is normal to it. Initially, it is assumed that the cylinder and fluid are at same temperature $T_w$ and concentration $C_w$. At $t' > 0$, the cylinder starts to move in the vertical direction with constant velocity $u_0$. The concentration level near the cylinder is raised to $C_w$. It is also assumed that there exists a homogeneous first order chemical reaction between the fluid and species
concentration. Here we assume the level of species concentration to be very low and hence heat generated during chemical reaction can be neglected. With these assumption the governing boundary layer equations can be written as

\[ \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} + \frac{g \beta (T' - T_\infty)}{\nu} + \frac{g \beta^*(C' - C_\infty)}{\nu} = \frac{1}{\nu} \frac{\partial u}{\partial t} \]  \hspace{1cm} (5.1)

\[ \frac{\partial^2 T'}{\partial r^2} + \frac{1}{r} \frac{\partial T'}{\partial r} = \frac{1}{\alpha} \frac{\partial T'}{\partial t} \]  \hspace{1cm} (5.2)

\[ \frac{\partial C'}{\partial t'} = \frac{D}{r} \left[ r \frac{\partial^2 C'}{\partial r^2} + \frac{\partial C'}{\partial r} \right] - k_i (C' - C_\infty) \]  \hspace{1cm} (5.3)

with boundary conditions

\[ t' \leq 0, \quad u = 0, \quad T' = T'_\infty, \quad C' = C'_\infty \quad for \quad all \quad r \]

\[ t' > 0, \quad u = u_0, \quad \frac{dT'}{dr} = -\frac{Q}{2\pi r_0 k}, \quad C' = C'_W \quad at \quad r = r_0 \]  \hspace{1cm} (5.4)

\[ u \to 0, \quad T' \to T'_\infty, \quad C' \to C'_\infty \quad as \quad r \to \infty \]

Introducing non-dimensional quantities

\[ R = \frac{r}{r_0}, \quad U = \frac{u}{u_0}, \quad l = \frac{t'v}{2}, \quad T = \frac{2\pi k (T' - T'_\infty)}{Q}, \quad C = \frac{C' - C'_\infty}{C'_W - C'_\infty}, \quad Pr = \frac{\nu}{\alpha}, \]  \hspace{1cm} (5.5)

\[ Sc = \frac{\nu}{D}, \quad Gr = \frac{g \beta Q r_0^2}{2\pi \nu ku_0}, \quad Gc = \frac{g \beta^*(C'_W - C'_\infty)r_0^2 \nu}{u_0}, \quad k_i = \frac{k_i r_0^2}{\nu} \]

The governing equations (5.1), (5.2) and (5.3) reduce to

\[ \frac{\partial^2 U}{\partial R^2} + \frac{1}{R} \frac{\partial U}{\partial R} + GrT + GcC = \frac{\partial U}{\partial t} \]  \hspace{1cm} (5.6)

\[ \frac{\partial^2 T}{\partial R^2} + \frac{1}{R} \frac{\partial T}{\partial R} = Pr \frac{\partial T}{\partial t} \]  \hspace{1cm} (5.7)
\[
\frac{\partial^2 C}{\partial R^2} + \frac{1}{R} \frac{\partial C}{\partial R} = Sc \left[ \frac{\partial C}{\partial t} + k_i C \right] \tag{5.8}
\]

And corresponding initial and boundary conditions are

\[
t < 0, \quad U = 0, \quad T = 0, \quad C = 0 \quad \text{for all} \ R
\]
\[
t > 0, \quad U = 1, \quad \frac{dT}{dR} = -1, \quad C = 1 \quad \text{at} \ R = 1
\]
\[
U \to 0, \quad T \to 0, \quad C \to 0 \quad \text{as} \ R \to \infty
\]  

\[(5.9)\]

5.3 Solution Technique:

To solve the above equations (5.6) – (5.8) subject to initial and boundary conditions (5.9), we apply Laplace transform technique. These equations give rise to

\[
\frac{d^2 \bar{U}}{dR^2} + \frac{1}{R} \frac{d \bar{U}}{dR} - s \bar{U} + Gr \bar{T} + G\bar{C} = 0 \tag{5.10}
\]

\[
\frac{d^2 \bar{T}}{dR^2} + \frac{1}{R} \frac{d \bar{T}}{dR} - s Pr \bar{T} = 0 \tag{5.11}
\]

\[
\frac{d^2 \bar{C}}{dR^2} + \frac{1}{R} \frac{d \bar{C}}{dR} - Sc(s + k_i)\bar{C} = 0 \tag{5.12}
\]

Where \(s\) is the parameter of Laplace transform defined by \(L\{f(t)\} = F(s)\), \(L\) being Laplace operator and \(\bar{U}, \bar{T}\) and \(\bar{C}\) are Laplace transform of \(U, T\) and \(C\) respectively.

We obtain the solutions of these equations (5.10), (5.11) and (5.12) subject to the transformed initial and boundary conditions for \(T\) and \(C\) in (5.9) are as follows

\[
\bar{T} = \frac{K_0(\sqrt{sPr}R)}{s\sqrt{sPr}K_1(\sqrt{sPr})} \tag{5.13}
\]

\[
\bar{C} = \frac{K_0(\sqrt{Sc(s + K_i)}R)}{sK_0(\sqrt{Sc(s + K_i)})} \tag{5.14}
\]

with the help of (5.13) and (5.14) and subject to transformed initial and boundary conditions for \(U\) in (5.9), we get the solution of the equation for \(Pr \neq 1, Sc \neq 1\) and for \(Pr=1, Sc=1\) as

\[(77)\]
\[ U = \frac{K_0(\sqrt{sR})}{sK_0(\sqrt{s})} + \frac{Gr}{s^{5/2}(Pr-1)\sqrt{Pr}} \left[ \frac{K_0(\sqrt{sPr})}{K_1(\sqrt{sPr})} \frac{K_0(\sqrt{sR})}{K_0(\sqrt{s})} - \frac{K_0(\sqrt{sPr})}{K_1(\sqrt{sPr})} \right] \]
\[ + \frac{G_c}{s\{Sc(s+k_i)-s\}} \left[ \frac{K_0(\sqrt{sR})}{K_0(\sqrt{s})} - \frac{K_0(\sqrt{Sc(s+k_i)R})}{K_0(\sqrt{Sc(s+k_i)})} \right] \]
\[ U = \frac{K_0(\sqrt{sR})}{sK_0(\sqrt{s})} + \frac{Gr}{2s^2} \left[ \frac{K_1(\sqrt{sR})}{K_1(\sqrt{s})} - \frac{K_0(\sqrt{sR})}{K_0(\sqrt{s})} \right] + \frac{G_c}{sk_i} \left[ \frac{K_0(\sqrt{sR})}{K_0(\sqrt{s})} - \frac{K_0(\sqrt{s+k_i}R)}{K_0(\sqrt{s+k_i})} \right] \] (5.15)

Now using the theorem of inverse Laplace transform for the equations (5.14), we get

\[ C = \frac{1}{2\pi i} \int_{-\infty}^{\infty} e^{st} \frac{K_0(R\sqrt{Sc(s+k_i)})}{K_0(\sqrt{Sc(s+k_i)})} ds \] (5.17)

The integrand has a branch point at \( s=0 \) and a simple pole at \( s=0 \) but \( K_0(\sqrt{Sc(s+k_i)}) \) do not have zeros at any point in the real and imaginary plane if the branch cut is made along the negative real axis. To obtain \( C(t, R) \) from \( \tilde{C}(s, R) \) requires a path as illustrated in fig. 5.1

Fig. 5.1

The line integral in (5.17) may be replaced by the limit of the sum of the integrals over FE, ED, DC, CB and BA as \( S_1 \to \infty \) and \( S_0 \to 0 \).

The particular form of the inversion integral, equation (5.17) has chosen because the values along paths DC, BA and FE tend to zero as \( S_1 \to \infty \) and \( S_0 \to 0 \).
Along the paths CB and ED, we choose $s = \frac{V^2}{Sc} e^{\iota \pi} - k$, and $s = \frac{V^2}{Sc} e^{-\iota \pi} - k$, respectively.

On the path CB,

$$C_{CB} = \frac{1}{\pi i} \int_0^\infty e^{-\frac{V^2}{Sc} + k} t \left\{ \frac{J_0(RV) - iY_0(RV)}{J_0(V) - iY_0(V)} \right\} \frac{VdV}{(V^2 + Sc k_t)}$$

(5.18)

Similarly on the ED

$$C_{ED} = \frac{1}{\pi i} \int_0^\infty e^{-\frac{V^2}{Sc} + k} t \left\{ \frac{J_0(RV) + iY_0(RV)}{J_0(V) + iY_0(V)} \right\} \frac{VdV}{(V^2 + Sc k_t)}$$

(5.19)

Adding the equations (5.18) and (5.19) give

$$C = C_{CB} + C_{ED} = \frac{2}{\pi} \int_0^\infty e^{-\frac{V^2}{Sc} + k} t \left\{ \frac{J_0(RV)Y_0(V) - Y_0(RV)J_0(V)}{J_0^2(V) + Y_0^2(V)} \right\} \frac{VdV}{(V^2 + Sc k_t)}$$

(5.20)

The residue of the integrand of the equation (5.17) at the simple pole at $s=0$ is 1.

Thus from the theory of residues, we get

$$C = 1 + \frac{2}{\pi} \int_0^\infty e^{-\frac{V^2}{Sc} + k} t \Gamma_1(R,V) \frac{VdV}{(V^2 + Sc k_t)}$$

(5.21)

Similarly, the inverse Laplace transforms of $\bar{T}$ and $\bar{U}$ in the equations (5.13), (5.15) and (5.16) becomes

$$T = \frac{2}{\pi} \int_0^\infty \left( 1 - e^{-\frac{V^2}{Pr}} \right) \frac{VdV}{V^2}$$

(5.22)

$$U = \frac{2}{\pi} \int_0^\infty \frac{\Gamma_1(R,V)}{V} \frac{VdV}{(V^2 + Pr)} + \frac{2Gr}{\pi \alpha} \int_0^\infty \left[ \frac{V^2}{Pr} + Pr(e^{-\frac{V^2}{Pr}} - 1) \right] \frac{VdV}{V^2}$$

$$+ \frac{2GcSe^{\kappa Pr}}{\pi} \left( 1 - e^{-\frac{V^2}{Sc} + k} \right) \frac{VdV}{V^2 + Sc k_t}$$

(5.23)
For \( Pr=Sc=1 \)

\[
U = 1 + \frac{2}{\pi} \int_0^\infty e^{-V^2 t} \Gamma_1(R,V) \frac{dV}{V} + \frac{Gr}{\pi} \int_0^\infty (1-e^{-V^2 t})[\Gamma_2(R,V) - \Gamma_1(R,V)] \frac{dV}{V^3}
\]

\[
\frac{2Ge}{\pi k_i} \int_0^\infty e^{-V^2 t} [\Gamma_1(R,\sqrt{V^2 + k_i}) - \Gamma_1(R,V)] \frac{VdV}{V^2 + k_i}
\]

Non dimensional skin friction \( \tau = \frac{\partial U}{\partial R} \) can be found from the equations (5.19) and (5.20) for \( Pr \neq 1, Sc \neq 1 \) and for \( Pr=Sc=1 \) respectively as

\[
\tau = \frac{2}{\pi} \int_0^\infty e^{-V^2 t} \frac{\Gamma_4(V)dV}{2Gr \pi(Pr-1)Pr} [\Gamma_3(V) - \Gamma_4(V)] \frac{dV}{V^3}
\]

Non dimensional Sherwood number \( Sh = \frac{\partial C}{\partial R} \) can be obtained from the equation (5.18)

\[
Sh = \frac{2}{\pi} \int_0^\infty e^{-V^2 t} \Gamma_4(V) \frac{dV}{V^2}
\]

(5.26)

Non dimensional Sherwood number \( Sh = \frac{\partial C}{\partial R} \) can be obtained from the equation (5.18)

\[
Sh = \frac{2}{\pi} \int_0^\infty e^{-V^2 t} \Gamma_4(V) \frac{dV}{V^2}
\]

(5.27)

where

\[
\Gamma_1(R,V) = \frac{J_0(RV)Y_0(V) - Y_0(RV)J_0(V)}{J_0^2(V) + Y_0^2(V)}
\]

\[
\Gamma_2(R,V) = \frac{J_1(RV)Y_1(V) - Y_1(RV)J_1(V)}{J_1^2(V) + Y_1^2(V)}
\]
\[ r_3(R, V) = \frac{J_0(RV)Y_1(V) - Y_0(RV)J_1(V)}{J_1^2(V) + Y_1^2(V)} \]
\[ \xi(R, V, \text{Pr}) = r_3(R, V) - \frac{\{J_1(V)Y_0(V) + Y_1(V)Y_0(V)\}J_0(RV)\sqrt{\text{Pr}}Y_0(V) - Y_0(RV)\sqrt{\text{Pr}}J_0(V)\sqrt{\text{Pr}})}{(J_1^2(V) + Y_1^2(V))(J_0^2(V)\sqrt{\text{Pr}} + Y_0^2(V)\sqrt{\text{Pr}})} \]
\[ 2\pi^2\left(\frac{J_0(RV)\sqrt{\text{Pr}}J_0(V)\sqrt{\text{Pr}} + Y_0(RV)\sqrt{\text{Pr}}Y_0(V)\sqrt{\text{Pr}}}{(J_1^2(V) + Y_1^2(V))(J_0^2(V)\sqrt{\text{Pr}} + Y_0^2(V)\sqrt{\text{Pr}})} \right) \]
\[ \Gamma_4(V) = \frac{J_1(V)Y_0(V) - J_1(V)J_0(V)}{J_0^2(V) + Y_0^2(V)} \]
\[ \Gamma_5(V) = \frac{\{J_1(V)Y_0(V) + Y_1(V)Y_0(V)\}(J_1(V)\sqrt{\text{Pr}}Y_0(V) - Y_1(V)\sqrt{\text{Pr}}J_0(V)\sqrt{\text{Pr}})}{2(J_1^2(V) + Y_1^2(V))} \]
\[ \Gamma_6(V) = \frac{\{J_1(V)Y_0(V) + Y_1(V)Y_0(V)\}(J_1(V)\sqrt{\text{Pr}}Y_0(V) - Y_1(V)\sqrt{\text{Pr}}J_0(V)\sqrt{\text{Pr}})}{2(J_1^2(V) + Y_1^2(V))(J_0^2(V)\sqrt{\text{Pr}} + Y_0^2(V)\sqrt{\text{Pr}})} \]

### 5.4 Results and Discussions:

For physical interpretation of the problem, the numerical computations are carried out for different physical parameters \( Gr, \ Gc, \ Sc, \ Pr, \ K, \) and \( t \) upon the nature of the flow and transport. The value of the Schmidt number \( Sc \) is taken to be 0.6 which corresponds to water-vapour. The values of Prandtl number \( Pr \) are chosen such that they represent air (\( Pr=0.71 \)) and water (\( Pr=7 \)). The numerical values of the velocity, temperature and concentration are computed for different physical parameters like Prandtl number, thermal Grashof number, mass Grashof number, chemical reaction parameter, Schmidt number and time are studied graphically.

Velocity profiles for different values of chemical reaction \( K \), are shown in figures 5.2 and 5.3. It is noted that the velocity increases with decreasing values of chemical reaction parameter \( K \). The effects of thermal Grashof number and mass Grashof number on velocity profiles for \( Pr=0.71, \ t=1.2 \) and \( K=0.5 \) are plotted in fig.5.4. The thermal Grashof number \( Gr \) signifies the relative effect of the buoyancy force to the hydrodynamic viscous force. The mass Grashof number \( Gc \) signifies the ratio of the species buoyancy force to the viscous hydrodynamic force. It is observed from the figure that velocity increases with increase of \( Gr \) & \( Gc \). In fig.5.5 we observe that there is a decrease in the velocity as Prandtl number \( Pr \) increases i.e.
for $Pr=0.71$ (air), 7.0 (water) also decreases with increase the values of Schmidt number $Sc$. Fig.5.6 depicts the velocity profiles at $Pr=0.71$, $Sc=0.6$ and $K_f=0.1$ for different values of time, which shows that velocity increases as time $t$ increases.

In fig. 5.7 it is observed that the temperature decreases with increase the value of prandtl number and increases with the increase the values of time $t$. The behaviour of temperature profiles for different values of Prandtl number with respect to time when $R=1.2$ is represented by fig.5.8. Here lower temperature profiles are observed for higher values of Prandtl number $Pr$. This is due to the fact that fluids with higher Prandtl number give rise to less heat transfer. Initially, it increases sharply but for higher value of time it becomes steady.

The concentration profiles for different values of the Schmidt number $Sc$ (=0.6, 0.4, 0.2), chemical reaction parameter $K_f=1$ and time $t=0.4$ are shown in fig.5.9. The effect of the Schmidt number is dominant in concentration field. It is noted that the concentration increases with decreasing values of Schmidt number $Sc$. Concentration profiles for various chemical reaction parameter $K_f$ are shown in fig.5.10. The effect of the chemical reaction parameter is dominant concentration field. It is seen that the concentration increases with increasing values of chemical reaction parameter $K_f$. In fig.5.11 concentration profiles for different Schmidt number $Sc$ and time $t$ at $K_f=0.2$ are drawn. It is observed that concentration increases with decrease the value of $Sc$ and increases with increase the value of $t$.

The effects of Schmidt number and Prandtl on skin friction are shown in fig.5.12. It is noted that the skin friction increases with increasing values of Schmidt numbers, but it decreases with increasing values of Prandtl number $Pr$. Skin friction for different values of chemical reaction parameter $K_f$ (=0.1, 1.0, 2.0), $Pr=0.71$, $Sc=0.6$ and $Gr=Gc=0.4$ are presented in fig.5.13. In this figure skin friction increases with increase in the values of $K_f$. Fig.5.14 exhibits the skin friction for different values of $Gr$ & $Gc$. The results show that the skin friction decreases with increasing values of $Gc$ and slowly increases with increasing values of $Gr$. Sherwood number for various parameters are shown in figs 5.15 and 5.16. Sherwood number decreases with increasing values of chemical reaction parameter $K_f$. But it increases with increase in Schmidt number.

5.5 Conclusions:

Transient free convection on a vertical cylinder under the combined buoyancy effects of heat flux and mass transfer along with first order chemical reaction parameter is studied analytically. The dimensionless governing equations are solved by the usual Laplace Transform technique. The effect of different physical parameters such as the thermal Grashof
number, mass Grashof number, chemical reaction parameter and time $t$ are studied graphically. Conclusions of this study are as follows:

I. It is observed that the velocity increases with increasing values of $Gr$. But trend is reversed with respect to the Schmidt number, Prandtl number and chemical reaction parameter.

II. Velocity decreases with increasing the values of chemical reaction parameter, but opposite effect is observed for concentration profile.

III. Velocity and temperature profiles are decreasing as $Pr$ increases.

IV. In case of $Sc$, the velocity and concentration profiles are decreasing as $Sc$ increases.

V. Skin friction increases with decrease in $Pr$ and increases with increase in $Sc$ and $K_r$.

VI. Sherwood number increases as $Sc$ increases but it decreases as $K_r$ increases.

Fig. 5.2 Transient velocity profiles for different values of $K_r$ when $Gr = Gc = 5$, $Pr = 0.71$, $Sc = 0.6$ and $t = 1.2$.
Fig. 5.3 Transient velocity profiles for different values of $K$, when $Gr = Gc = 5$, $Pr = 1$, $Sc = 0.6$ and $t = 1.2$

Fig. 5.4 Velocity profiles for different values of $Gr$ and $Gc$ when $Sc = 0.6$, $t = 1.2$, $Pr = 0.1$ and $K = 0.5$

(84)
Fig. 5.5 Velocity profiles for different Sc when $Gr = Gc = 5, t = 1.2, K_r = 1$ and $Pr = 7$

Fig. 5.6 Effects of time on velocity profiles for $Gr = Gc = 5, r = 0.71, Sc = 0.6$ and $K_r = 0.1$
Fig. 5.7 Temperature profiles for different \( Pr \)

Fig. 5.8 Effects of Prandtl number on temperature profiles with respect to time at \( R=1.2 \)
Fig. 5.9 Effects of $Sc$ on concentration profiles for $t=1.4$ and $K_f=0.2$

Fig. 5.10 Concentration profiles for different $K_f$ when $Sc=0.8$, $R=1.4$
Fig. 5.11 Concentration profiles for different $Sc$ and $t$ when $K_r=0.2$

Fig. 5.12 Skin friction for $Gr=Gc=0.4$, $K_r=0.2$
Fig. 5.13 Skin friction for various values of $K_t$ when $Pr=0.71$, $Sc=0.6$ and $Gr=Gc=0.4$

Fig. 5.14 Skin friction for different values of $Gr$ and $Gc$ at $Pr=1$, $Sc=0.6$ and $k_f=0.2$
Fig. 5.15 Sherwood number for different values of $K_i$ at $Sc=0.6$

Fig. 5.16 Effects of $Sc$ on Sherwood number for $\xi^*=0.1$. 

Fig. 5.16 Effects of $Sc$ on Sherwood number for $k_i=0.1$. 

(90)