CHAPTER 3

Soret and Dufour effects on heat and mass transfer in Darcy-Forchheimer MHD mixed convection from a vertical flat plate embedded in a fluid saturated porous medium with the effects of radiation and Thermophoresis

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CHAPTER 3

3.1 Introduction

The studies in aerosol deposition have become more and more important for engineering applications. The factors that influence particle deposition include convection, Brownian diffusion, turbulence, sedimentation, inertial effect, thermophoresis, electrophoresis, and surface geometry respectively.

Goldsmith and May [40] first studied the thermophoretic transport involved in a simple one-dimensional flow for the measurement of the thermophoretic velocity. The phenomenon where particles are influenced by the thermophoretic force is called thermophoresis. The thermophoretic force is caused by differences in the velocity distribution of the gas molecules. Therefore the velocity distribution of the gas particles must be found to calculate the net momentum transfer by Aitken [3]. Selim et al. [96] studied the effect of surface mass flux on mixed convective flow past a heated vertical flat permeable plate with thermophoresis. Thermophoresis particle deposition effect was analyzed by Chamka et al. [20]. Hossain and Takhar [47] analyzed the effect of radiation using the Rosseland diffusion approximation. Damesh et al. [25] studied the effect of radiation and heat transfer in different geometry for various flow conditions. K.Govardhan et al. [44] studied viscous dissipation and radiation.

The effects of Dufour, Soret were neglected in many reported research studies. The energy flux can be generated by the
temperature gradients and the composition gradients. The mass transfer caused by the temperature gradient is called the Soret effect, while the heat transfer caused by the concentration gradient is called the Dufour effect (Eckert and Drak [31]). The Dufour and Soret effects were studied by many researchers. Eldabe et al. [32], studied the flow in boundary layer includes the temperature which dependent on viscosity with thermal-diffusion and diffusion-thermo effects.

D. Srinivasacharya et al. [103] presented the effect of Soret and Dufour on mixed convection in a non-Darcy porous medium saturated with micro polar fluid.

The present work aims to investigate the simultaneous effects of thermophoresis, radiation, viscous dissipation, Soret and Dufour on MHD mixed convective heat and mass transfer from a vertical flat plate embedded in a saturated porous medium with thermal and mass diffusion. The governing coupled equations are solved by using implicit finite difference scheme with C-programming code.

3.2 Mathematical formulation

Consider steady, viscous incompressible fluid flow with radiating and hydro magnetic fluid flow bounded by a vertical flat plate embedded in a fluid-saturated porous medium. The x-coordinate is measured along the plate from its leading edge and the y-coordinate is normal to it. Assuming that the fluid to be Newtonian, electrically conductive, wall temperature is $T_w$ and concentration is $C_w$ which is firmly surrounded in a fluid saturated porous. The concentration $C_\infty$ and ambient temperature $T_\infty$, where $T_w > T_\infty$ and $C_w > C_\infty$ respectively.
Boussinesq approximation [56] and the Rosseland approximation [89] is used to explain the radiative heat flux in the energy equation. A uniform transverse magnetic field of strength $\beta_0$ is applied parallel to the $y$ axis. Under the above assumption, the governing equation for this problem can be written as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$ (3.2.1)

$$\left[ 1 + \frac{\sigma \beta_0^2 K_1}{\rho \nu} \right] \frac{\partial u}{\partial y} + \frac{c_f \sqrt{K_1}}{v} \frac{\partial (u^2)}{\partial y} = \pm g \frac{k_1}{v} \left[ \beta_T \frac{\partial T}{\partial y} + \beta_C \frac{\partial C}{\partial y} \right]$$ (3.2.2)

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_m \frac{\partial^2 T}{\partial y^2} + \frac{\nu}{c_p} \left( \frac{\partial u}{\partial y} \right) - \frac{1}{\rho c_p} \frac{\partial q_r}{\partial y} - \frac{\partial}{\partial y} \left( V_T T \right)$$

$$+ \frac{\partial m \kappa_T \partial x}{c_s c_p \partial y^2}$$ (3.2.3)

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_m \frac{\partial^2 C}{\partial y^2} - \frac{\partial}{\partial y} \left( V_T C \right) + \frac{\partial m \kappa_T \partial T}{T_m \partial y^2}$$ (3.2.4)

The boundary conditions are given by

$$v = 0, \quad T = T_w, \quad C = C_w \text{ as } y = 0$$

$$u = u_\infty, \quad T = T_\infty, \quad C = C_\infty \text{ as } y = \infty$$ (3.2.5)

$u$ velocity components is in $x$ direction, $v$ velocity components is in $y$ direction, $T$ is the temperature, $C$ is the concentration, $c_f$ is the Forchheimer coefficient, $\sigma$ is the conductivity of the fluid, $c_p$ is the specific heat at constant pressure, $C_s$ is the concentration susceptibility, $\rho$ is the density, $D_m$ is the mass diffusivity, $K_1$ is the Darcy permeability, $\nu$ is the kinematic viscosity, $\beta_C$ is the coefficient of concentration expansion, $\beta_T$ is the coefficient of thermal expansion, $q_r$ is the radiative heat flux, $K_T$ is the thermal diffusion ratio and $T_m$ is the mean fluid temperature.
In Equation (3.2.2), the plus sign corresponds to the case where the buoyancy has a component “aiding” the forced flow and minus sign refers to the “opposing” case.

By using the Rosseland approximation for radiation [84] and following Raptis [87], radiative heat flux $q_r$ is given by

$$q_r = -\frac{16\sigma_1 T_y^3}{3k_e} \frac{\partial T}{\partial y} \quad (3.2.6)$$

where $\sigma_1$ is the Stefan-Boltzmann constant, $k_e$ the mean absorption coefficient and $T_\infty$ the temperature of the ambient fluid.

In Equations (3.2.3) and (3.2.4) the thermophoretic velocity $V_T$ was defined by Talbot et al [107]

$$V_T = -k_v \frac{\nabla T}{T} = -\frac{k_v}{T} \frac{\partial T}{\partial y}$$

where $k_v$ is the thermophoretic coefficient, which was defined by Batchelor [12]

With using Eq. (3.2.6) and Eq. (3.2.3) gives

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_m \frac{\partial^2 T}{\partial y^2} + \frac{v}{c_p} \left( \frac{\partial u}{\partial y} - \frac{\partial}{\partial y} (V_T) \right) + \frac{16\sigma_1 T_y^2}{3p c_p k_e} \frac{\partial^2 T}{\partial y^2} + \frac{\partial}{\partial y} \left( \frac{p k_T}{T_m} \frac{\partial T}{\partial y^2} \right) \quad (3.2.7)$$

we define dimensionless variables as

$$\eta = \sqrt{\frac{\rho}{\rho_\infty}} \frac{y}{x}, \quad \psi = \alpha_m \sqrt{\frac{\rho}{\rho_\infty}} f(\eta),$$

$$\theta(\eta) = (T - T_\infty)/(T_w - T_\infty),$$

$$\phi(\eta) = (C - C_\infty)/(C_w - C_\infty) \quad (3.2.8)$$

In the above equation

$\psi$ is the stream function, $\eta$ is the dimensionless similarity variable and continuity equation is satisfied by $\psi$. 
Using Eq. (3.2.8) the changes of variables, Eqs. (3.2.2), (3.2.4) and (3.2.7) are transformed to

\[(1 + Ha^2)f'' + 2Af f' = \pm \left(\frac{Ra}{Pe_x}\right)(\theta' + N\phi)\]  

\[\theta\left(1 + \frac{4}{3R}\right) + \frac{1}{2}f \theta' + PrE \theta'^2 - \tau Pr(\theta \theta' + \theta'^2) + Df \phi' = 0\]  

\[\phi' + \frac{3}{2}Le f' - \tau Sc(\theta \phi' + \phi \theta') + Le_S \phi' = 0\]

The corresponding boundary conditions are

\[f(\eta) = 0, \quad \theta(\eta) = 1, \quad \phi(\eta) = 1\] \text{on } \eta = 0

\[f'(\eta) \rightarrow 1, \theta(\eta) \rightarrow 0, \phi(\eta) \rightarrow 0\text{ as }\eta \rightarrow \infty\]  

Where prime denotes the differentiation with respect to \(\eta\),

\[\text{Pe}_x = \frac{u_x x}{\alpha_m}\] local Peclet number

\[\text{Sc} = \frac{v}{D_m}\] Schmidt number

\[\text{Ra}_x = \frac{(K_1 \beta_T)(T_w - T_x)x}{\alpha v}\] thermal Rayleigh number

\[N = \frac{\beta_e (C_w - C_x)}{\beta_T (T_w - T_x)}\] buoyancy ratio parameter

\[\Lambda = c_f \sqrt{K_1 u_x / \nu}\] inertia parameter

\[\text{Ha}^2 = \sigma \beta_0^2 K_1 / \rho v\] magnetic parameter

\[R = \frac{k k_e}{4 \sigma_1 T_x^3}\] radiation parameter

\[k\] thermal conductivity

\[\text{Le} = \frac{\alpha_m}{D_m}\] Lewis number

\[D_f = D_m k_T (C_w - C_x) / \alpha_m C_s C_p (T_w - T_x)\] Dufour number

\[S_r = D_m k_T (T_w - T_x) / \alpha_m T_m (C_w - C_x)\] Soret number

\[\text{Ec} = u_x^2 / c_p (T_w - T_x)\] Eckert number

\[\tau = -k(T_w - T_x) / T\] Thermophoretic parameter

\[\text{Pr} = \frac{\nu}{\alpha_m}\] Prandtl number
The Nusselt number is defined by
\[ \text{Nu}_x = \frac{q_w x}{(T_w - T_x)k} = -\frac{1}{2} Pe_x^\frac{1}{2} \theta'(0); \]
\[ q_w = -k \frac{\partial T}{\partial y} \bigg|_{y=0} \]  \hspace{1cm} (3.2.13)

The Sherwood number is defined by
\[ \text{Sh}_x = \frac{J_w x}{(c_w - c_x)D_m} = -Pe_x^\frac{1}{2} \phi'(0); \]
\[ J_w = -D_m \frac{\partial c}{\partial y} \bigg|_{y=0} \]  \hspace{1cm} (3.2.14)

### 3.3 Numerical solution

We integrate the system of ordinary differential equations, Eqs.(3.2.9)-(3.2.11), with the boundary conditions in Eq. (3.2.12) numerically by means of implicit finite difference method. Applying the Quasi-linearization technique, Bellman and Kalaba [14] to the non-linear equation (3.2.9) we obtain
\[
(1 + H a^2 + 2 H F') f' + 2 \lambda F^2 f = \pm \left( \frac{\text{Ra}_x}{\text{Pe}_x} \right) \left( \theta' + N \phi' \right) + 2 \lambda F' F' \]  \hspace{1cm} (3.3.1)

Where assumed \( F \) is the value of \( f \) at \( n \)th iteration and \( f \) is at \( (n+1) \)th iteration. The convergence criterion is fixed as \( |F_n f| < 10^{-5} \).

The equations (3.3.1),(3.2.10) and (3.2.11), become with the implementation of implicit finite difference scheme
\[
\alpha \begin{bmatrix} f[i-1] + b_1[i] f[i] + c_1[i] f[i+1] \end{bmatrix} = d_1[i] \]  \hspace{1cm} (3.3.2)
\[
\alpha_1 \begin{bmatrix} \theta[i-1] + b_1[i] \theta[i] + c_1[i] \theta[i+1] \end{bmatrix} = d_1[i] \]  \hspace{1cm} (3.3.3)
\[
\alpha_2 \begin{bmatrix} \phi[i-1] + b_2[i] \phi[i] + c_2[i] \phi[i+1] \end{bmatrix} = d_2[i] \]  \hspace{1cm} (3.3.4)

where
\[ a[i] = 1 + Ha^2 + 2 \lambda F_1[i] - 0.5h^2 \lambda F_2[i] \]

\[ b[i] = -2(1 + Ha^2 + 2 \lambda F_1[i]) \]

\[ c[i] = 1 + Ha^2 + 2 \lambda F_1[i] + 0.5h^2 \lambda F_2[i] \]

\[ d[i] = h^2 h^2 \pm \left( \frac{Ra_x}{Pr_x} \right) (\theta_1 + N\phi_1) + 2 \lambda F_2[i]F_1[i] \]

\[ a_1[i] = 1 + (4/3R) - \tau Pr \theta - 0.5h^2 0.5F[i] - 2\tau Pr\theta_1[i] \]

\[ b_1[i] = -2 * (1 + (4/3R) - \tau Pr \theta) + h^2 h^2 \tau Pr\theta_2[i] \]

\[ c_1[i] = 1 + (4/3R) - \tau Pr \theta + 0.5h^2 0.5F[i] - 2\tau Pr\theta_1[i] \]

\[ d_1[i] = h^2 h^2 - Pr Ec f_2[i] f_2[i] - D_f^2 \phi_2[i] - \tau Pr\theta_1[i] \theta_1[i] - \tau Pr\theta_1[i] \theta_2[i] \]

\[ a_2[i] = 1 - 0.5h^2 (0.5F[i] \theta_1) - \tau Sc \theta_1[i] \]

\[ b_2[i] = -2 - h^2 h^2 \tau Sc \theta_2[i] \]

\[ c_2[i] = 1 + 0.5h^2 (0.5F[i] \theta_1) - \tau Sc \theta_1[i] \]

\[ d_2[i] = h^2 h^2 - Le S_r \theta_2[i] \]

\[ A[i] = 1 + Ha^2 + 2 \lambda F_1[i] \]

\[ B[i] = 2 \lambda F_2[i] \]

\[ D[i] = \pm \left( \frac{Ra_x}{Pr_x} \right) (\theta_1 + N\phi_1) + 2 \lambda F_2[i]F_1[i] \]

\[ A_1[i] = 1 + (4/3R) - \tau Pr \theta \]

\[ B_1[i] = 0.5F[i] - 2\tau Pr\theta_1[i] \]

\[ C_1[i] = -\tau Pr\theta_2[i] \]

\[ D_1[i] = -Pr Ec f_2[i] f_2[i] - \tau Pr\theta_1[i] \theta_1[i] - \tau Pr\theta_1[i] \theta_2[i] - D_f^2 \phi_2[i] \]

\[ A_2[i] = 1, \]

\[ B_2[i] = 0.5F[i] - Le Sc \theta_1[i] \]

\[ C_2[i] = -\tau Sc \theta_2[i] \]

\[ D_2[i] = Le S_r \theta_2[i] \]

The set of equations (3.3.2)-(3.3.4) are coupled equations, which are solved by using the Gauss Seidel iteration method by using the C-
programming code. The iterative procedure is initiated by the solution of concentration equation followed by energy equation and momentum equation which is continued until convergence is achieved. To get a converged solution and it was set to $10^{-5}$ for dependent variable $f'$, $\theta$, $\phi$. The mesh sizes are taken as $h = 0.0005$ and $h = 0.0025$, computed the values and analyzed that the numerical values are same for both mesh sizes. Hence, we conclude that the finite difference method is convergent.

### 3.4 Results and discussion

The numerical computations have been carried for various governing parameters such as magnetic parameter $H_a$, mixed convection parameter $Ra_x/Pe_x$, radiation parameter $R$, inertia parameter $\Lambda$, Prandtl number $Pr$, Lewis number $Le$, Soret $Sr$ and Dufour $Df$, Schmidt number $Sc$, thermophoretic number $\tau$ and buoyancy ratio parameter $N$. In addition, the edge of the boundary layer $\eta\to\infty$ was approximated by $\eta_{\text{max}} = 6$, which was sufficiently large to reach the relevant stream velocity. In figures 3.6.1 to 3.6.12, depict profiles such as velocity, temperature and concentration. The Prandtl number $Pr$ are chosen $Pr = 0.73$ which corresponds to air. The values of other parameters fixed as $Ra_x/Pe_x = 1$, $R = 0.5$, $\Lambda = 0.1$, $Pr = 0.73$, $Le = 2$, $Sc = 1$, $\tau = 0.5$, $N = 2$, $Ec = 0.5$, $Sr = 2$, $Df = 0.03$. Fig.3.6.1 display the effect of magnetic parameter $H_a$ on profiles such as velocity, temperature and concentration. It is evident from the figure the velocity profile $f'$ decreases with the increase of magnetic parameter $H_a$. The temperature and concentration profiles increase
with the increase of magnetic parameter $H_a$. It is because that applications of transverse magnetic field will result a resistive type of force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity.

Figure (3.6.2) illustrates the influence of the mixed convection parameter $Ra_x/Pe_x$ on velocity, temperature and concentration profiles respectively. In fact, for mixed convection parameter, if $Ra_x/Pe_x \gg 1$ flow is natural convection and $Ra_x/Pe_x \ll 1$, flow leads to forced convection, $Ra_x/Pe_x = 1$, fluid flow becomes mixed convection. From fig.(3.6.2) it is noticed that with the increasing $Ra_x/Pe_x$, the velocity profile $f'$ increase while temperature and concentration profiles decreases.

Dimensionless profiles of velocity, temperature and concentration are drawn in fig. (3.6.3) for radiation parameter $R$. The radiation parameter $R$ increases leads to decrease the velocity profiles $f'$, temperature profiles $\theta$ within the boundary layer as well as thickness of the velocity and temperature boundary layer. This is because for large value of radiation parameter corresponds to an increased dominance of conduction over radiation, thereby decreasing buoyancy force, thickness of the thermal, momentum boundary layers. The effect of radiation parameter $R$ is very meagre on concentration profile.

Figure (3.6.4) depicts the effect of inertia parameter $\Lambda$ on velocity, temperature and concentration profiles. From the figure the velocity profile decrease with increasing inertia parameter $\Lambda$, whereas
temperature and concentration profiles increases. The reason for this behavior is that the inertia of the porous medium provides an additional resistance to the fluid flow mechanism, which causes the fluid to move at a retarded rate with reduced temperature and concentration.

It is found from figure 3.6.5(a) the velocity profile $f'$ increases with increasing the buoyancy ratio parameter $N$, while the temperature and concentration profiles decreases with the effect of $N$ is observed from figures 3.6.5(b) and 3.6.5(c). This nature because of buoyancy ratio increase the surface heat and mass transfer rates.

The effect of Soret and Dufour is shown in figure (3.6.6). From figure 3.6.6(a) and (b) the velocity and temperature increase when Dufour number increase (or decrease of Soret number) whereas reverse phenomena is observed in concentration profile which is showed in fig.3.6.6(c).

Figure (3.6.7) displayed the effect of Eckert number on various profiles. It can be founded profiles of velocity, temperature and concentration increase with the increase of Eckert number Ec. The effect of viscous dissipation and flow fixed is to increase the energy, resulting a greater fluid temperature and as a consequence greater buoyancy force.

It can be observed from figure (3.6.8) the velocity distribution $f'$ and concentration profile $\phi$ decreases with the increasing of thermophoretic parameter $\tau$. 
The effect of Lewis number Le for the velocity and concentration profile inside the boundary layer region displayed in the figure (3.6.9). It can be noticed form the figure that the velocity and concentration profiles decreases with the increase of Lewis number Le.

Figure (3.6.10) concerns with the effect of Schmidt number Sc on the concentration profile. The concentration profile decrease with an increase Sc, physically it is true. The increase of Sc means decrease of molecular diffusivity that results in decrease of concentration boundary layer. Thus, the concentration of species is lower for higher values of Sc and higher for small values of Sc.

Figure 3.6.11(a)-(b) displays the influence of radiation parameter R and Eckert number Ec on the Local Nusselt number \( \frac{\text{Nu}_x}{\sqrt{\text{Pe}_x}} \) as a function of mixed convection parameter \( \frac{\text{Ra}_x}{\text{Pe}_x} \). It can be seen from this the local Nusselt number \( \frac{\text{Nu}_x}{\sqrt{\text{Pe}_x}} \) increases with radiation parameter \( R \) and decreases with \( Ec \). The effect of radiation parameter the local Nusselt number \( \frac{\text{Nu}_x}{\text{Pe}_x^{1/2}} \) increases in forced convection but decreases in natural convection.

The local Sherwood number \( \frac{\text{Sh}_x}{\text{Pe}_x^{1/2}} \) as a function of \( \frac{\text{Ra}_x}{\text{Pe}_x} \) is shown in fig.3.6.12 for the various values of radiation parameter \( R \). The effect of radiation parameter \( R \) is to reduce the Sherwood number \( \frac{\text{Sh}_x}{\text{Pe}_x^{1/2}} \) in the natural convection (\( \frac{\text{Ra}_x}{\text{Pe}_x} \gg 1 \)) and the reverse phenomenon is observed in forced convection (\( \frac{\text{Ra}_x}{\text{Pe}_x} \ll 1 \)).
Fig. 3.6.1 Effects of magnetic parameter $Ha$ for $Ra_x/Pe_x = 1, R = 0.5, \Lambda = 0.1, Pr = 0.73, Le = 2, Sc = 1, \tau = 0.5, N = 2, Ec = 0.5, S_r = 2, D_l = 0.03$ profiles of (a) Velocity (b) Temperature (c) Concentration
Fig. 3.6.2 Effects of mixed parameter $Ra_x/Pe_x$ for $\Lambda=0.1$, $R=0.5$, $N=2$, $Pr=0.73$, $Le=2$, $Sc=1$, $\tau=0.5$, $Ec=0.5$, $Ha=0$, $Sr=2.0$, $Dr=0.03$ profiles of (a) Velocity (b) Temperature (c) Concentration
Fig. 3.6.3 Effects of Radiation parameter $R$ for $\Lambda = 0.1$, $Ra_x/Pe_x = 1$, $N=2$, $Pr=0.73$, $Le=2$, $Sc=1$, $\tau=0.5$, $Ha=0$, $Ec=0.5$, $Sr = 2.0$, $Df = 0.03$ profiles of (a) Velocity (b) Temperature (c) Concentration
**Fig. 3.6.4** Effects of inertia parameter $\Lambda$ for $Ra_x/Pe_x=1$, $R=0.5$, $N=2$, $Pr=0.73$, $Le=2$, $Sc=1$, $\tau=0.5$, $Ha=0$, $Ec=0.5$, $Sr=2$, $D_f=0.03$ profiles of (a) Velocity (b) Temperature (c) Concentration
Fig. 3.6.5 Effects of buoyancy ratio parameter $N$ for $Ra_x/Pe_x=1$, $R=0.5$, $\Lambda=0.1$, $Pr=0.73$, $Le=2$, $Sc=1$, $Ec=0.5$, $Sr=2$, $Di=0.03$, $\tau=0.5$, $Ha=0$ profiles of
(a) Velocity (b) Temperature (c) Concentration
Fig. 3.6.6 Effects of Soret and Dufour for $Ra_x/Pe_x = 1$, $R = 0.5$, $Λ = 0.1$, $Pr = 0.73$, $Le = 2$, $Ha = 0$, $Ec = 0.5$, $τ = 0.5$, $Sc = 1$, $N = 2$ on (a) Velocity profile (b) Temperature profile (c) Concentration profile
Fig. 7(a) 

Fig. 7(b) 

Fig. 7(c) 

Fig. 3.6.7 Effects of Eckert number for $Ra_x/Pe_x=1$, $R=0.5$, $\Lambda=0.1$, $Pr=0.73$, $Le=2$, $Ha=0$, $Sc=1$, $\tau=0.5$, $S_r=2.0$, $D_r=0.03$, $N=2$ on
(a) Velocity profile
(b) Temperature profile
(c) Concentration profile
Fig. 3.6.8 Effects of thermophoresis $\tau$ for $Ra_{x}/Pe_{x} = 1$, $R = 0.5$, $\Lambda = 0.1$, $Pr = 0.73$, $Le = 2$, $Ha = 0$, $Sc = 1$, $N = 2$, $Ec = 0.5$, $Sr = 2$, $Df = 0.03$ on
(a) Velocity profile (b) Concentration profile
Fig. 3.6.9 Effects of Lewis number for $\frac{Ra_x}{Pe_x} = 1$, $R=0.5$, $\Lambda=0.1$, $Pr=0.73$, $Sc=1$, $Ha=0$, $Ec=0.5$, $\tau=0.5$, $N=2$, $D_t = 0.03$ profiles of (a) Velocity (b) Concentration.
Fig. 3.6.10  Effects of Schmidt number Sc for $\frac{Ra_x}{Pe_x}=1$, $R=0.5$, $\Lambda=0.1$, $Pr=0.73$, $Le=2$, $Ha=0$, $\tau=0.5$, $N=2$ $Ec=0.5$, $Sr=2$, $Df=0.03$ on Concentration profile

Fig. 11(a) Effect of Nusselt Number for various values of Radiation $R$ and $Ec$ $\Lambda=0.1$, $Pr=0.73$, $Sc=1$, $Ha=0$, $Le=2$, $\tau=0.5$, $N=2$, $Sr=2.0$, $Df=0.03$
Fig. 3.6.1
Effect of Sherwood number for various of Radiation
\( \text{Ra} \), \( \Lambda = 0.1 \), \( \text{Pr} = 0.73 \), \( \text{Sc} = 1 \), \( \text{Ha} = 0 \), \( \text{Ec} = 0.5 \), \( \text{Le} = 2 \), \( \tau = 0.5 \), \( N = 2 \), \( \text{Ec} = 0.5 \), \( S_r = 2.0 \), \( D_f = 0.03 \)

\[ \text{Sh}_x / \text{Pe}_x^{1/2} \]

\[ \text{Ra}_x / \text{Pe}_x \]

Fig. 12

- \( R = 0.2 \)
- \( R = 1.0 \)
- \( R = 2.0 \)