CHAPTER-5

COMBINED INFLUENCE OF THERMAL RADIATION, SORET AND DUFOUR EFFECTS ON NON-DARCY MIXED CONVECTIVE HEAT AND MASS TRANSFER FLOW WITH DISSIPATIVE IN A VERTICAL CHANNEL.

5.1. INTRODUCTION:

The vertical channel is an often encountered configuration in thermal engineering equipment, as an example, collectors of solar power, cooling devices of digital and micro-digital equipments and many others. Gill and Casal [193] have made an analysis on the influence of electrically conducting the case of fully developed mixed convection between horizontal parallel plates with a linear axial temperature distribution. The problem of fully developed mixed convection between vertical plates with and without heat sources was solved by Ostrach [194]. Cebeci et al., [195] performed numerical calculations of developing laminar mixed convection between vertical parallel plates for both cases of buoyancy aiding and opposing conditions. Al-Nimir and Haddad [59] have described the fully developed free convection in an open-ended vertical channel partially filled with porous material. Greif et al [60] have made an analysis on the laminar convection of a radiating gas in a vertical channel. The radiation effect on a hydromagnetic convective flow in a vertical channel was studied by Gupta and Gupta [61]. Datta and Jana [62] have studied the effect of wall conductance on a hydromagnetic convection of a radiation gas in a vertical channel. The combined forced and free convective flow in a vertical channel with viscous dissipation and isothermal – isoflux boundary conditions have been studied by Barletta [63]. Barletta et al [64] have presented a dual mixed convection flow in a vertical channel. Barletta et al [65] have described a buoyancy MHD flow in a vertical channel.

Non-Darcy effects on natural convection in porous media have received a great deal of attention in recent years because of the experiments conducted with several combinations of solids and fluids covering wide ranges of governing parameters which indicate that the experimental data for systems other than glass water at low Rayleigh numbers, do not agree with theoretical predictions based on the Darcy flow model. Extensive effects are thus being made to include the inertia and
viscous diffusion terms in the flow equations and to examine their effects in order to
develop a reasonable accurate mathematical model for convective transport in porous
media. The work of Vafai and Tien [66] was one of the early attempts to account for the
boundary and inertia effects in the momentum equation for a porous medium. Vafai and
Thiyagarajau [67] presented analytical solutions for the velocity and temperature fields
for the interface region using the Brinkman Forchheimer–extended Darcy equation.
Detailed accounts of the recent efforts on non-Darcy convection have been recently
reported in Tien and Hong [68], Cheng [69] and Kalidas and Prasad [70].

Recently Ravindra et al (149) have discussed Non-Darcy convective heat and mass transfer in a vertical channel with thermal radiation and
dissipation.

In this chapter we investigate the combined influence of the
soret and dufour effect on the flow phenomenon. The non linear coupled equations
governing the flow have been solved by Galerkin finite element analysis. The effect of sr
and du on all the flow characteristics has been exhibited graphically. It is found that an
increase in Sr (or decrease in Du) results in an enhancement velocity u and actual
temperature and depreciates in the actual concentration. In the absence of Sr=0 and
Du=0, the results are compared with Ravindra et al (149).

5.2. FORMULATION OF THE PROBLEM:

A completely evolved laminar convective heat and mass
exchange stream of a viscous, electrically conducting fluid through the permeable strata
kept in a vertical channel enclosed by flat walls is considered. We pick a Cartesian co-
dordinate system O(x, y, z) with x- axis in the vertical bearing and y-axis ordinary to the
walls, the walls are taken at y=±L. The walls are kept up at steady temperature and
concentration. The temperature slant in the stream field is sufficient to motive natural
convection in the stream field. A steady axial pressure slant is furthermore constrained so
that this resultant stream is a blended convection stream. The porous medium is thought
to be isotropic and homogeneous with relentless porosity and viable thermal diffusivity.
The thermo physical properties of porous network are moreover thought to be consistent
and Boussinesq estimation is conjured by means of restricting the density variety to the
buoyancy term. Without any superfluous force, stream is in the same direction along the x-axis which is thought to be interminable.

The Darcy model is valid only for relatively slow flows through a porous matrix. In general, we must consider the effect of fluid inertia, boundary effect, and the viscous diffusion, which may well become significant for materials with very high porosities such as fibrous media and foams and the medium consisting of spare distribution of particles. Hence the Brinkman-Forchheimer-extended Darcy model that accounts for the inertia and boundary effects has been used for the momentum equation in the porous region.

By employing the Oberbeck–Boussinesq and the standard boundary layer approximations, the Darcy-Forchheimer model, the momentum equation in the scalar form is (Chamka [155], Mallikarjuna [156])

\[
\begin{align*}
-\frac{\partial p}{\partial x} + \left(\frac{\mu}{\delta}\right) \frac{\partial^2 u}{\partial y^2} - \left(\frac{\mu}{k}\right)u - \left(\frac{\sigma \mu^2 H^2}{\rho_e}\right)u - \frac{\rho \delta F}{\sqrt{k}} u^2 - \rho g &= 0 \\
\end{align*}
\]

(5.2.1)

Where \(-\frac{\partial p}{\partial x}\) is represent pressure gradient, \(\left(\frac{\mu}{\delta}\right) \frac{\partial^2 u}{\partial y^2}\) is represent viscous force, \(-\left(\frac{\mu}{k}\right)u\) is represent Darcy force, \(-\left(\frac{\sigma \mu^2 H^2}{\rho_e}\right)u\) is represent Lorentz force, \(-\frac{\rho \delta F}{\sqrt{k}} u^2\) is represent inertia and boundary effect, \(-\rho g\) is represent Buoyancy term.

Energy and diffusion equations in the scalar form are

\[
\begin{align*}
\rho_0 C_p \frac{\partial u}{\partial x} &= k_f \frac{\partial^2 T}{\partial y^2} - \frac{\partial (q_v)}{\partial y} + \mu \left(\frac{\partial u}{\partial y}\right)^2 + \frac{D_m K_T}{C_p C_x} \frac{\partial^2 C}{\partial y^2} \\
\end{align*}
\]

(5.2.2)

\[
\begin{align*}
u \frac{\partial C}{\partial x} &= D_m \frac{\partial^2 C}{\partial y^2} - k_f C + \frac{D_m K_T}{T_m} \frac{\partial^2 \theta}{\partial y^2} \\
\end{align*}
\]

(5.2.3)

Where \(u\), \(T\), \(C\), \(\mu\), \(\delta\), \(k\), \(\sigma\), \(H_0\), \(F\), \(g\), \(C_p\), \(\rho_0\), \(q_v\), \(D_m\), \(K_T\), \(k_f\), \(T_m\) are characterized in the nomenclature area of this thesis.
The relevant boundary conditions are

\[ u = 0, \quad T = T_w, \quad C = C_w \text{ at } y = \pm L \quad (5.2.4) \]

By applying Ressoland approximation (Brewester [153]) the radiative heat flux \( q_r \) is given by

\[ q_r = -\left( \frac{4\sigma^*}{3\beta_R} \right) \frac{\partial}{\partial y} \left[ T'^4 \right] \quad (5.2.5) \]

Where \( \sigma^* \) is the Stephan–Boltzmann constant and mean absorption coefficient.

Assuming that the difference in temperature within the flow, such that \( T'^4 \) can be expressed as a linear combination of the temperature. We expand \( T'^4 \) in Taylor’s series about \( T_e \) as follows

\[ T'^4 = T_0^4 + 4T_0^3(T - T_0) + 6T_0^2(T - T_0)^2 + ..... \quad (5.2.6) \]

Neglecting higher order terms beyond the first degree in \( (T - T_0) \). We have
\[ T^{r4} = -3T_0^4 + 4T_0^3T \] (5.2.7)

Differentiating equation (5.2.5) with respect to \( y \) and using (5.2.7) we get

\[ \frac{\partial (q_r)}{\partial y} = -\frac{16\sigma^r T_0^3}{3\beta_R} \frac{\partial^2 T}{\partial y^2} \] (5.2.8)

Using (5.2.8) equation (5.2.2) reduces to

\[ \rho_0 C_p u \frac{\partial T}{\partial x} = (k_f + \frac{16\sigma^r T_0^3}{3\beta_R}) \frac{\partial^2 T}{\partial y^2} + \mu \frac{\partial u}{\partial y} + \frac{D m K_r}{C_r C_p} \frac{\partial^2 C}{\partial y^2} \] (5.2.9)

Following Tao [167] and Das [150], we assume that the temperature and concentration of the both walls is \( T_w = T_0 + Ax, \ C_w = C_0 + Bx \) where \( A \) and \( B \) are the vertical temperature and concentration gradients which are positive for buoyancy–aided flow and negative for buoyancy–opposed flow, respectively, \( T_0 \) and \( C_0 \) are the upstream reference wall temperature and concentration respectively. The velocity depend only on the radial coordinate and all the other physical variables except temperature, concentration and pressure are functions of \( y \) and \( x \), \( x \) being the vertical co-ordinate.

The temperature and concentration inside the fluid can be written as

\[ T = T^*(y) + Ax, \quad C = C^*(y) + Bx \]

We define the following non-dimensional variables as

\[ u' = \frac{u}{(\nu / L)}, \quad (x', y') = (x, y) / L, \quad p' = \frac{p\delta}{(\rho \nu^2 / L^2)} \]

\[ \theta(y) = \frac{T^*-T_0}{P_{AL}}, \quad C = \frac{C^*-C_0}{P_{BL}}, \quad P_i = \frac{dp}{dx} \] (5.2.10)

Introducing these non-dimensional variables the governing equations in the dimensionless form reduce to (on dropping the dashes)

\[ \frac{d^2 u}{dy^2} = 1 + \delta (M_i^2) u - \delta G(\theta + NC) - (\delta^2 \Delta) u^2 \] (5.2.11)

Where \( \delta \) and \( \Delta \) are parameters.

\[ (1 + \frac{4RD}{3}) \frac{d^2 \theta}{dy^2} = (P_r) u + Ec Pr \frac{du}{dy}^2 - Du Pr \frac{d^2 C}{dy^2} \] (5.2.12)

\[ \frac{d^2 C}{dy^2} - \gamma C = (Sc) u - ScSr \frac{d^2 \theta}{dy^2} \] (5.2.13)
Where

\[ \Delta = FD^{-1/2} \]  \quad \text{(Inertia or Forchheimer parameter)}

\[ G = \frac{\beta g A L^3}{\nu^2} \]  \quad \text{(Grashof Number)}

\[ D^{-1} = \frac{L^2}{k} \]  \quad \text{(Inverse Darcy parameter)}

\[ Sc = \frac{\nu}{D_i} \]  \quad \text{(Schmidt number)}

\[ N = \frac{B^* B}{\beta A} \]  \quad \text{(Buoyancy ratio)}

\[ P_i = \frac{\mu C_p}{k_f} \]  \quad \text{(Prandtl Number)}

\[ \gamma = \frac{k_i L^2}{D_i} \]  \quad \text{(Chemical reaction parameter)}

\[ Rd = \frac{4\sigma^* T_e^3}{3\beta k_f} \]  \quad \text{(Radiation Parameter)}

\[ Ec = \frac{\nu^2}{P_i A L C_p} \]  \quad \text{(Eckert number)}

\[ Sr = \frac{D_m K_f A}{k_f T_m B} \]  \quad \text{(Soret Parameter)}

\[ Du = \frac{D_m K_f B}{C_s C_p A} \]  \quad \text{(Dufour Parameter)}

\[ M^2 = \frac{\sigma \mu^2 H_0^2 L^2}{\nu} \]  \quad \text{(Hartmann number)}

\[ M_1^2 = M^2 + D^{-1} \]

The corresponding boundary conditions are

\[ u = 0 \quad \theta = 0 \quad C = 0 \quad \text{on} \quad y = \pm 1 \]  \quad (5.2.14)

### 5.3. FINITE ELEMENT ANALYSIS:

Using finite element technique, these differential equations are evaluated with the corresponding boundary conditions, we assume if \( u^i, \theta^i, c^i \) are the estimations of \( u, \theta \) and \( C \) we describe the errors (residual) \( E_u^i, E_o^i, E_c^i \) as

\[ E_u^i = \frac{d}{dy} \left( \frac{du^i}{dy} \right) - M_1^2 u^i + \delta^2 \Delta (u^i)^2 - \delta G (\theta^i + NC^i) \]  \quad (5.3.1)

\[ E_c^i = \frac{d}{dy} \left( \frac{dC^i}{dy} \right) - \gamma C^i - Scu^i - ScSr \frac{d}{dy} \left( \frac{d\theta^i}{dy} \right) \]  \quad (5.3.2)

\[ E_o^i = (1 + \frac{4Rd}{3}) \frac{d}{dy} \left( \frac{d\theta^i}{dy} \right) - P_i u^i - Pr Ec \left( \frac{du^i}{dy} \right)^2 - Du Pr \frac{d}{dy} \left( \frac{dC^i}{dy} \right) \]  \quad (5.3.3)
Where

\[ u^i_k = \sum_{k=1}^{3} u_k \psi_k, \quad C^i = \sum_{k=1}^{3} C_k \psi_k, \quad \theta^i = \sum_{k=1}^{3} \theta_k \psi_k \]  

(5.3.4)

These errors are orthogonal to the weight function over the domain of \( e_i \) under Galerkin finite element technique we choose the approximation functions as the weight function. Multiply each term of the equations (5.2.11-5.2.13) by the weight function i.e. each of the approximation function \( \psi^i_j \) and integrate over the typical tri-nodal linear element \((\eta_e, \eta_{e+1})\). We obtain

\[ \int_{\eta_e}^{\eta_{e+1}} \left( \frac{d}{dy} \left( \frac{du^i}{dy} \right) \right) - M^2 \theta^i + \delta^2 (\theta^i)^2 - \delta G(\theta^i + NC^i(\theta^i)) \psi^i dy = 0 \]  

(5.3.5)

\[ \int_{\eta_e}^{\eta_{e+1}} \left( \frac{d}{dy} \left( \frac{dC^i}{dy} \right) \right) - \gamma C^i - Scu^i + ScSr \left( \frac{d}{dy} \left( \frac{d\theta^i}{dy} \right) \right) \psi^i dy = 0 \]  

(5.3.6)

\[ \int_{\eta_e}^{\eta_{e+1}} \left( (1 + \frac{4Rd}{3}) \frac{d}{dy} \left( \frac{d\theta^i}{dy} \right) \right) - P_c u^i - P_c Ec (\frac{d\theta^i}{dy})^2 + Du Pr \left( \frac{dC^i}{dy} \right) \psi^i dy = 0 \]  

(5.3.7)

Choosing different \( \Psi^i_j \)'s corresponding to each element \( \eta_e \) in the equation (5.3.5)-(5.3.7) yields a local stiffness matrix of order 3×3 in the form

\[ \begin{pmatrix} f^i_{1,1} & g^i_{1,1} & e^i_{1,1} \\ g^i_{2,1} & m^i_{2,1} & t^i_{2,1} \\ e^i_{3,1} & t^i_{3,1} & p^i_{3,1} \end{pmatrix} - \delta G(g^i_{1,1})(\theta^i_{1,1} + NC^i_{1,1}) + \delta M^2(\theta^i_{2,1})(\theta^i_{3,1}) + \delta^2 (\theta^i_{1,1})^2 + \delta^2 (\theta^i_{2,1})^2 + \delta G(\theta^i_{1,1} + NC^i_{1,1}) \psi^i_{1,1} = (Q^i_{1,1} + Q^i_{2,1}) \]  

(5.3.8)

\[ \begin{pmatrix} e^i_{1,1} - \gamma C^i \\ C^i \\ Sc(m^i_{2,1})(\theta^i_{1,1}) + ScSr(t^i_{2,1})(\theta^i_{3,1}) \end{pmatrix} = (R^i_{1,1} + R^i_{2,1}) \]  

(5.3.9)

\[ (1 + \frac{4Rd}{3})(\theta^i_{1,1} + \theta^i_{2,1} + \theta^i_{3,1}) - (P_c (1 + Ec)(\theta^i_{1,1}) + Du Pr (\theta^i_{1,1} + Ec)(\theta^i_{2,1} + \theta^i_{3,1} + \theta^i_{4,1}) = S^i_{1,1} + S^i_{2,1} \]  

(5.3.10)

Where \( \begin{pmatrix} f^i_{1,1} \end{pmatrix}, \begin{pmatrix} g^i_{1,1} \end{pmatrix}, \begin{pmatrix} e^i_{1,1} \end{pmatrix}, \begin{pmatrix} m^i_{2,1} \end{pmatrix}, \begin{pmatrix} t^i_{2,1} \end{pmatrix}, \begin{pmatrix} e^i_{3,1} \end{pmatrix}, \begin{pmatrix} t^i_{3,1} \end{pmatrix}, \begin{pmatrix} p^i_{3,1} \end{pmatrix}, \begin{pmatrix} r^i_{2,1} \end{pmatrix} \) are 3×3 matrices and \( \begin{pmatrix} Q^i_{1,1} \end{pmatrix}, \begin{pmatrix} Q^i_{2,1} \end{pmatrix}, \begin{pmatrix} R^i_{1,1} \end{pmatrix}, \begin{pmatrix} R^i_{2,1} \end{pmatrix}, \begin{pmatrix} S^i_{1,1} \end{pmatrix} \) and \( \begin{pmatrix} S^i_{2,1} \end{pmatrix} \) are 3×1 column matrices and such stiffness matrices in terms of local nodes in each element are assembled using inter element continuity and equilibrium conditions to obtain the coupled global matrices in terms of the global nodal values of u, \( \theta \) & C((5.3.8)-(5.3.10)). The resulting coupled stiffness matrices are solved by iteration process. This process is frequently repeated till the successive values of \( u_i \)'s, \( \theta_i \)'s and \( C_i \)'s differ by a pre assigned percentage.
The shape functions corresponding to

\[ \psi_1 = \frac{(y-4)(y-8)}{32} \]
\[ \psi_2 = \frac{(y-2)(y-4)}{8} \]
\[ \psi_3 = \frac{(3y-4)(3y-8)}{32} \]
\[ \psi_4 = \frac{(y-1)(y-2)}{2} \]
\[ \psi_5 = \frac{(5y-4)(5y-8)}{32} \]

\[ \psi_2 = \frac{(y-6)(y-8)}{8} \]
\[ \psi_3 = \frac{(3y-12)(3y-16)}{32} \]
\[ \psi_2 = \frac{(y-10)(y-12)}{8} \]
\[ \psi_4 = \frac{(y-3)(y-4)}{2} \]
\[ \psi_5 = \frac{(5y-12)(5y-16)}{32} \]

\[ \psi_3 = \frac{(y-20)(y-24)}{32} \]
\[ \psi_4 = \frac{(y-5)(y-6)}{2} \]

\[ \psi_5 = \frac{(5y-20)(5y-24)}{32} \]

5.4. STIFFNESS MATRICES:

The global matrix for

\[ \theta \text{ is } A_3 \begin{bmatrix} x_3 \end{bmatrix} = B_3 \]  \hspace{1cm} (5.4.1)

\[ C \text{ is } A_4 \begin{bmatrix} x_4 \end{bmatrix} = B_4 \]  \hspace{1cm} (5.4.2)

\[ u \text{ is } A_5 \begin{bmatrix} x_5 \end{bmatrix} = B_5 \]  \hspace{1cm} (5.4.3)

Where
$A_3 = \begin{pmatrix}
-1 & a_{1,2} & a_{1,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & a_{2,2} & a_{2,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & a_{3,2} & a_{3,3} & a_{3,4} & a_{3,5} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & a_{4,3} & a_{4,4} & a_{4,5} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & a_{5,3} & a_{5,4} & a_{5,5} & a_{5,6} & a_{5,7} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a_{6,5} & a_{6,6} & a_{6,7} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & a_{7,5} & a_{7,6} & a_{7,7} & a_{7,8} & a_{7,9} \\
0 & 0 & 0 & 0 & 0 & 0 & a_{8,7} & a_{8,8} & a_{8,9} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a_{9,7} & a_{9,8} & a_{9,9} & a_{9,10} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{10,9} & a_{10,10} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{11,9} & a_{11,10} & -1
\end{pmatrix}$

$A_4 = \begin{pmatrix}
1 & b_{1,2} & b_{1,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & b_{2,2} & b_{2,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & b_{3,2} & b_{3,3} & b_{3,4} & b_{3,5} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & b_{4,3} & b_{4,4} & b_{4,5} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & b_{5,3} & b_{5,4} & b_{5,5} & b_{5,6} & b_{5,7} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & b_{6,5} & b_{6,6} & b_{6,7} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & b_{7,5} & b_{7,6} & b_{7,7} & b_{7,8} & b_{7,9} & 0 \\
0 & 0 & 0 & 0 & 0 & b_{8,7} & b_{8,8} & b_{8,9} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & b_{9,7} & b_{9,8} & b_{9,9} & b_{9,10} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & b_{10,9} & b_{10,10} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & b_{11,9} & b_{11,10} & b_{11,11}
\end{pmatrix}$
\[ A_3 = \begin{bmatrix}
1 & a_{1,2} & a_{1,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & a_{2,2} & a_{2,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & a_{3,2} & a_{3,3} & a_{3,4} & a_{3,5} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & a_{4,3} & a_{4,4} & a_{4,5} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & a_{5,3} & a_{5,4} & a_{5,5} & a_{5,6} & a_{5,7} & 0 & 0 & 0 \\
0 & 0 & 0 & a_{6,5} & a_{6,6} & a_{6,7} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & a_{7,5} & a_{7,6} & a_{7,7} & a_{7,8} & a_{7,9} & 0 \\
0 & 0 & 0 & 0 & 0 & a_{8,7} & a_{8,8} & a_{8,9} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & a_{9,7} & a_{9,8} & a_{9,9} & a_{9,10} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{10,9} & a_{10,10} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{11,9} & a_{11,10} & a_{11,11}
\end{bmatrix} \]

\[ B_3 = \begin{bmatrix}
a_{i_1} \\
a_{i_2} \\
a_{i_3} \\
a_{i_4} \\
a_{i_5} \\
a_{i_6} \\
a_{i_7} \\
a_{i_8} \\
a_{i_9} \\
a_{i_{10}} \\
a_{i_{11}}
\end{bmatrix} \quad B_2 = \begin{bmatrix}
b_{i_1} \\
b_{i_2} \\
b_{i_3} \\
b_{i_4} \\
b_{i_5} \\
b_{i_6} \\
b_{i_7} \\
b_{i_8} \\
b_{i_9} \\
b_{i_{10}} \\
b_{i_{11}}
\end{bmatrix} \quad B_1 = \begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
f_4 \\
f_5 \\
f_6 \\
f_7 \\
f_8 \\
f_9 \\
f_{10} \\
f_{11}
\end{bmatrix} \quad X_3 = \begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4 \\
\theta_5 \\
\theta_6 \\
\theta_7 \\
\theta_8 \\
\theta_9 \\
\theta_{10} \\
\theta_{11}
\end{bmatrix} \quad X_4 = \begin{bmatrix}
C_1 \\
C_2 \\
C_3 \\
C_4 \\
C_5 \\
C_6 \\
C_7 \\
C_8 \\
C_9 \\
C_{10} \\
C_{11}
\end{bmatrix} \quad X_5 = \begin{bmatrix}
\psi_1 \\
\psi_2 \\
\psi_3 \\
\psi_4 \\
\psi_5 \\
\psi_6 \\
\psi_7 \\
\psi_8 \\
\psi_9 \\
\psi_{10} \\
\psi_{11}
\end{bmatrix} \]

In fact that the non-linear term is arises in the modified Brinkman linear momentum equation of the porous medium. The iteration process is taking the global matrices is as follows. We cut up the square term into a product term and retaining one of them say \( u_i \)'s under integration, the another one is expanded in terms of local nodal values, resulting in the consequent coefficient matrix \( (n^k_{i,j}, s) \), whose coefficients include the unknown \( u_i \)'s. To calculate the initial global nodal values of \( u_i \)'s as zeros in the zeroth estimation. We evaluate \( u_i \)'s, \( \theta_i \)'s and \( C_i \)'s in the normal procedure stated earlier. Later selecting those values of \( u_i \)'s as first order approximation calculate \( \theta_i \)'s, \( C_i \)'s. In the second iteration, we substitute for \( u_i \)'s the first order approximation of and \( u_i \)'s and the first approximation of \( \theta_i \)'s and \( C_i \)'s get second order approximation. This process is
repeated till the successive values of $u_i$’s, $\theta_i$’s and $C_i$’s differ by a pre assigned percentage. For computational purpose we choose five elements in flow region.

Shear Stress, Nusselt Number and Sherwood Number are defined as

The shear stress on the boundaries $y = \pm 1$ is given by

$$\tau_{y=\pm L} = \mu \left( \frac{du}{dy} \right)_{y=\pm L}$$

In the non-dimensional form is

$$\tau_{y=\pm 1} = \left( \frac{du}{dy} \right)_{y=\pm 1}$$

The rate of heat transfer (Nusselt Number) is given by

$$Nu_{y=\pm 1} = \left( \frac{d\theta}{dy} \right)_{y=\pm 1}$$

The rate of mass transfer (Sherwood Number) is given by

$$Sh_{y=\pm 1} = \left( \frac{dC}{dy} \right)_{y=\pm 1}$$

5.5. COMPARISON TABLE:

In the absence of thermo-diffusion (Sr=0) and Diffusion-thermo (Du=0) the results are found to be in good agreement with that of Ravindra et al (149).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ravidra et al(149)</th>
<th>Present Results</th>
</tr>
</thead>
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5.6. DISCUSSION OF THE NUMERICAL RESULTS:

In order to get physical insight into the problem we have carried out numerical calculations for non-dimensional velocity, temperature and species concentration, skin-friction, Nusselt number and Sherwood number by assigning some particular values to the parameters \( N, \alpha, \gamma, F, Ec, Sr, Du \) and \( \Delta \). In this analysis, we emphasize the effect of soret and dufour on the flow characteristics.

i. Effects of parameters on velocity profiles:

Fig.5.7.1a displays the variation of the velocity \( u \) with buoyancy ratio \( (N) \). It is found that when the molecular buoyancy force dominates over the thermal buoyancy force the axial velocity reduces when the buoyancy forces are in the same direction and for the forces acting in opposite directions it increases. This may be attributed to the fact that the thickness of the momentum boundary layer reduces with \( N>0 \) and enhances with \( N<0 \). Fig.5.7.2a & 5.7.3a shows that the variation of the velocity \( u \) with heat source parameter \( (\alpha) \). It is found that an increase in the strength of the heat generating source larger the velocities in the whole flow region. This is due to the fact that energy is generated in the boundary layer, which leads to an enhancement in \( u \). Heat is absorbed in the boundary layer which results in the reduction of the velocity. The effect of chemical reaction parameter \( (\gamma) \) on \( u \) is shown in fig.5.7.5a&5.7.6a. It is found that the axial velocity enhances with increase in \( \gamma \) in the entire flow region in the degenerating chemical reaction case \( (\gamma>0) \) while in the generating chemical reaction case \( (\gamma<0) \). Fig.5.7.7a shows the variation of the velocity \( u \) with Eckert number \( Ec \). It is found that higher the dissipative effect, smaller the axial velocity in the flow region. This is due to the fact that the energy is absorbed in the fluid. The variation of the velocity \( u \) with Soret parameter \( Sr/Dufour \) parameter \( Du \) is displayed in fig.5.7.8a. It can be seen from the profiles that enhancing Soret parameter \( Sr \) (or decreasing Dufour parameter \( Du \)) larger the axial velocity. This is due to the fact that an increase in \( Sr \) (or decrease in \( Du \)) increases the thickness of the momentum. Fig.5.7.9a represents the velocity \( u \) with Forchheimer number \( \Delta \). It is found that the axial velocity depreciates with increasing \( \Delta \). In this manner the inclusion of inertia effects reduces the axial velocity.
ii. Effects of parameters on temperature profiles:

The non-dimensional temperature (θ) is displayed in figs.5.7.1b-5.7.9b for different parametric representations. We follow the convention that the non-dimensional temperature (θ) is positive/negative according as the actual temperature (T*) is greater/lesser than the reference temperature T0. Fig.5.7.1b displays the variation of θ with buoyancy ratio (N). It is seen from profile, the actual temperature reduces with N irrespective of the directions of the buoyancy forces in the flow region. This is because of energy is absorbed in the thermal boundary layer with increase |α|. Fig.5.7.2b, fig.5.7.3b, and fig.5.7.4b represents the variation of θ with heat source parameter (α) and F. It is analyzed from profiles that an enhancement in the strength of the heat generating/absorption source leads to depreciation in the actual temperature in the flow region. Fig.5.7.5b&5.7.6b represents θ with chemical reaction parameter (γ). From the profiles we found that the actual temperature decreases with increase in γ in the degenerating chemical reaction case, while in the generating chemical reaction case the actual temperature enhances with increase in |γ|≤1.5 and higher |γ|≥2.5 we see the depreciation in the actual temperature. Fig.5.7.7b shows θ with Ec. Higher the dissipation larger the actual temperature. This is due to the fact that the thermal energy is generated in the fluid on account of frictional heating. Hence, the temperature distribution rises in the entire thermal boundary layer. The variation of θ with Soret parameter (Sr) and Dufour parameter Du is displayed in fig.5.7.8b. It can be seen from the profiles that an increase in Sr(or decreasing Du) larger the actual temperature. This is due to the fact that the thickness of thermal boundary layer increases with increase in Sr (or decrease in Du). Fig.5.7.9b shows θ with Forchheimer number (Δ). We find that from the figure the actual temperature enhances with increase in Δ. Thus the inclusion of the inertia effects increases the actual temperature.

iii. Effects of parameters on concentration profiles:

The non-dimensional concentration (C) is displayed in figs.5.7.1c-5.7.9c for different parametric variations. We follow the convention that the non-dimensional concentration (C) is positive/negative according as the actual concentration (c*) is greater/lesser than the reference concentration (C0). Fig.5.7.1c
demonstrates the variation of C with buoyancy ratio N. The actual concentration depreciates with N>0 and the forces acting in opposite directions it enhances. This is may be attributed the fact that the thickness of the solutal boundary layer decreases with N>0 and increases with |N| (<0). Fig.5.7.2c&5.7.3c demonstrates the variation of C with heat source parameter (α). An increase in the strength of the heat generating/absorbing source leads to decrease in the actual concentration. This may be due to the fact that the thickness of thermal boundary layer decreases with increase |α| as energy is absorbed in the boundary layer. Fig.5.7.5c&5.7.6c express the variation of C with Chemical reaction parameter (γ). It can be seen from the profiles that the actual concentration decreases in the degenerating chemical reaction case, while in the generating chemical reaction case the actual concentration reduces with |γ|≤1.5 and higher |γ|≥2.5 we notice that an enhancement in the actual concentration. Fig.5.7.7c shows C with Ec. It can be seen from the profiles that higher the dissipation larger the actual concentration. This is due to the fact that energy is generated in the solutal boundary layer. Fig.5.7.8c represents the variation of C with Sr and Du. We found that from the profiles an increase in the Soret parameter Sr(or decreasing Du) smaller the actual concentration in the entire flow region. This may be attributed to the fact that an enhancement in Sr (or depreciation in Du) results in depreciation in the thickness of the solutal boundary layer. Fig.5.7.9c represents the concentration with Forchheimer number (∆). We find that the inclusion of inertia effects depreciates the actual concentration in the flow region.

iv. Effects of parameters on Skin friction, Nusselt number and Sherwood number (table 5.8.1):

The Skin friction, the rate of heat and mass transfer at the boundaries y=±1 is exhibited in table.5.8.1. The skin friction enhances on y=±1 with increase in the strength of the heat generating source, while it depreciates with strength of the heat absorption source. When the molecular buoyancy force dominates over the thermal buoyancy force the skin friction depreciates on the walls, when the buoyancy forces are in the same direction and for the forces acting in opposite directions it increases on the walls. With reference to the chemical reaction parameter (γ) we find that
the skin friction enhances on both the walls in both the degenerating/generating chemical reaction cases. Higher the radiative heat flux smaller the skin friction on walls. The variation of $\tau$ with $Sr$ and $Du$ demonstrates that increase in $Sr$ (or decreasing $Du$) depreciates $\tau$ on both the walls. An increase in $Ec$ enhances the skin friction on the walls. Thus higher the dissipative effect lesser the skin friction on the walls. The variation of $\tau$ with Forchheimer number $\Delta$ shows that the consideration of the inertia effects leads to a reduction in the skin friction on both the walls.

The Nusselt number decreases on the walls with increasing in the buoyancy ratio ($N>0$). When the buoyancy forces are in the same direction and forces acting in opposite directions it increases on the walls. The magnitude of $Nu$ reduces on $y=\pm 1$ with an enhancement in the strength of the heat generating source, while it increases with heat absorption source. By concerning the chemical reaction parameter ($\gamma$) we find that the magnitude of $Nu$ decreases in the degenerating chemical reaction case and enhances in the generating chemical reaction case on both walls. Higher the radiative heat flux smaller the rate of heat transfer. The Nusselt number reduces with enhancing $Ec\leq 0.05$ smaller the Nusselt number and with higher $Ec\geq 0.07$, $Nu$ increases on the walls. An increase in Soret parameter $Sr$ (or decreasing $Du$) decreases the Nusselt number on both the walls. The consideration of the inertia effects ($\Delta$) leads to a reduction in $Nu$ and also lesser the thermal diffusivity larger the rate of heat transfer at both the walls.

The Sherwood number depreciates with increasing $\alpha>0$ on $y=\pm 1$, while a reversed effect is noticed for $\alpha<0$. With regard to the chemical reaction parameter ($\gamma$) we find that the rate of mass transfer decreases on $y=\pm 1$ in degenerating chemical reaction case, while in the generating chemical reaction case it enhances on the walls. The rate of mass transfer reduces with increase in $N>0$ and increases with $N<0$ on both the walls. Higher the radiative heat flux larger $|Sh|$. With respect to Soret parameter $Sr$ and Dufour parameter $Du$ we find that increase in $Sr$ (or decreasing $Du$) enhances the rate of mass transfer on both the walls. The variation of $Sh$ with $Ec$ displays the rate of mass transfer increases with increase in $Ec$. Consideration of the inertia effects ($\Delta$) leads to an enhancement in $Sh$. 
5.7 GRAPHS:

Fig. 5.7.1a Variation of velocity $u$ for different values of Buoyancy ratio $N$ 
($\alpha=2$, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)

Fig. 5.7.1b Variation of temperature $\theta$ for different values of Buoyancy ratio $N$ 
($\alpha=2$, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)
Fig.5.7.1c Variation of concentration $C$ for different values of Buoyancy ratio $N$ $(\alpha=2, \gamma=0.5, F=0.5, Ec=0.01, Sr=0.5, Du=0.3, \Delta=2)$

Fig.5.7.2a Variation of velocity $u$ for different values of Heat source parameter $\alpha > 0$ $(N=0.5, \gamma=0.5, F=0.5, Ec=0.01, Sr=0.5, Du=0.3, \Delta=2)$
Fig. 5.7.2b Variation of temperature $\theta$ for different values of Heat source parameter $\alpha > 0$
($N=0.5$, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)

Fig. 5.7.2c Variation of concentration $C$ for different values of Heat source parameter $\alpha > 0$
($N=0.5$, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)
Fig. 5.7.3a Variation of velocity $u$ for different values of Heat source parameter $\alpha < 0$
(N=0.5, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)

Fig. 5.7.3b Variation of temperature $\theta$ for different values of Heat source parameter $\alpha < 0$
(N=0.5, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)
Fig 5.7.3c Variation of concentration $C$ for different values of Heat source parameter $\alpha < 0$ 
(N=0.5, $\gamma=0.5$, $F=0.5$, Ec= 0.01, Sr=0.5, $Du=0.3$, $\Delta=2$)

Fig 5.7.4a Variation of velocity $u$ for different values of $F$ 
(N=0.5, $\alpha=2$, $\gamma=0.5$, Ec= 0.01, Sr=0.5, $Du=0.3$, $\Delta=2$)
Fig. 5.7.4b: Variation of temperature $\theta$ for different values of $F$
(N=0.5, $\alpha=2$, $\gamma=0.5$, Ec= 0.01, Sr=0.5, Du=0.3, $\Delta=2$)

Fig. 5.7.4c: Variation of concentration $C$ for different values of $F$
(N=0.5, $\alpha=2$, $\gamma=0.5$, Ec= 0.01, Sr=0.5, Du=0.3, $\Delta=2$)
Fig. 5.7.5a Variation of velocity $u$ for different values of Chemical reaction parameter $\gamma > 0$
(N=0.5, $\alpha$=2, $F$=0.5, $E_c$= 0.01, $Sr$=0.5, $Du$=0.3, $\Delta$=2)

Fig. 5.7.5b Variation of temperature $\theta$ for different values of Chemical reaction parameter $\gamma > 0$
(N=0.5, $\alpha$=2, $F$=0.5, $E_c$= 0.01, $Sr$=0.5, $Du$=0.3, $\Delta$=2)
Fig. 5.7.5c Variation of concentration C for different values of Chemical reaction parameter $\gamma > 0$
(N=0.5, $\alpha=2$, F=0.5, Ec= 0.01, Sr=0.5, Du=0.3, $\Delta=2$)

Fig. 5.7.6a Variation of velocity u for different values of Chemical reaction parameter $\gamma < 0$
(N=0.5, $\alpha=2$, F=0.5, Ec= 0.01, Sr=0.5, Du=0.3, $\Delta=2$)
Fig. 5.7.6b Variation of velocity $\theta$ for different values of chemical reaction parameter $\gamma < 0$
(N=0.5, $\alpha=2$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$, $\Lambda=2$)

Fig. 5.7.6c Variation of concentration $C$ for different values of Chemical reaction parameter $\gamma < 0$
(N=0.5, $\alpha=2$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$, $\Lambda=2$)
Fig. 5.7.7a. Variation of velocity $u$ for different values of Eckert number $Ec$ 
($N=0.5$, $\alpha=2$, $\gamma=0.5$, $F=0.5$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)

Fig. 5.7.7b. Variation of temperature $\theta$ for different values of Eckert number $Ec$ 
($N=0.5$, $\alpha=2$, $\gamma=0.5$, $F=0.5$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)
Fig. 5.7.7c. Variation of concentration $C$ for different values of Eckert number $Ec$
(N=0.5, $\alpha=2$, $\gamma=0.5$, $F=0.5$, $Sr=0.5$, $Du=0.3$, $\Delta=2$)

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Fig. 5.7.8a. Variation of velocity $u$ for different values of $Sr$ & $Du$
(N=0.5, $\alpha=2$, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $\Delta=2$)
**Fig. 5.7.8b.** Variation of temperature $\theta$ for different values of Sr & Du
(N=0.5, $\alpha=2$, $\gamma=0.5$, $F=0.5$, Ec=0.01, $\Delta=2$)

**Fig. 5.7.8c.** Variation of concentration $C$ for different values of Sr and Du
(N=0.5, $\alpha=2$, $\gamma=0.5$, $F=0.5$, Ec=0.01, $\Delta=2$)
Fig. 5.7.9a. Variation of velocity $u$ for different values of Forchheimer parameter $\Delta$
($N=0.5$, $\alpha=2$, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$)

Fig. 5.7.9b. Variation of temperature $\theta$ for different values of Forchheimer parameter $\Delta$
($N=0.5$, $\alpha=2$, $\gamma=0.5$, $F=0.5$, $Ec=0.01$, $Sr=0.5$, $Du=0.3$)
Fig. 5.7.9c. Variation of concentration C for different values of Forchheimer parameter Δ
(N=0.5, α=2, γ=0.5, F=0.5, Ec=0.01, Sr=0.5, Du=0.3)

5.8. TABLE:

Table 5.8.1: Skin Friction (τ), Nusselt Number (Nu) and Sherwood Number (Sh) at
y=±1

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</tbody>
</table>