Chapter 6

The Influence of Lateral Mass Flux on Mixed Convection Heat Mass Transfer Over Inclined Surfaces in Porous Media

6.1 Introduction


The effect of lateral mass flux on mixed convection boundary layer flow and heat trans-
fer has received good attention in recent past. Initial steps were taken by Horne and O’Sullivan[8], Cheng and Lau[9], and Cheng and Techchandani[10] with numerical approaches. They studied the effects of withdrawal of fluids in hot water geothermal reservoirs. Later Schoch and Laird[11] have performed an experimental study on the simultaneous withdrawal and injection of fluids in porous medium. Lai and Kulacki[12,13] have investigated the effects of surface injection/suction on heat transfer in mixed convection over horizontal and inclined surfaces under similar boundary layers flow conditions. They reported the influence of forced flow on pure free convection and effect of buoyancy on forced convection. However, they did not use a single parameter which had controlled the entire regime of mixed convection, while they reported the limiting cases of pure natural and pure forced convection. Later Hooper, Chen and Armaly[14] have done it numerically. They obtained non-similar solutions for uniform suction/injection with single parameter which is valid for entire mixed convection regime. They predicted that suction increases the rate of heat transfer, whereas injection decreases it on the wall.

Thus mixed convection heat transfer study in porous media has received considerable concentration. However the mixed convection problems in coupled heat and mass transfer has received almost no act of courtesy. So the main aim of the present study is to initiate the similarity analysis to study the effect of injection/withdrawal of fluid for boundary layer heat and mass transfer along inclined surfaces embedded in fluid saturated porous media which is based on the Darcy’s model. It is found that similarity solutions exist when wall temperature, concentration and free stream velocity vary according to the same power function of of distance i.e. $x^\lambda$. Non-dimensional parameter $Gr$ is used to represent the effects of mixed convection through out the entire regime (from pure natural to pure forced convection). Additionally the mass flux parameter $f_w$ gives a measure of injection ($f_w > 0$) or the suction ($f_w < 0$) effect. The cases when the flow and buoyancy forces are in the same direction and when they are in opposite directions are discussed. In the former case flow develops from mainly forced convection near the leading edge to mainly free convection far downstream. An appropriate heat and mass transfer formulae for mixed convection surface injection/suction which covers all possible ranges of mass flux
parameter \( f_w \), Grashof number \( Gr \), bouyancy ratio \( N \) and Lewis number \( Le \) is obtained and studied in detail. Analytical solutions are obtained for mixed convection heat and mass transfer from an isothermal vertical plate \( (\lambda = 0) \) as well as inclined plate with constant heat flux having an inclined angle \( 45^\circ \) \( (\lambda = 1/3) \) and to study the stagnation flow \( (\lambda = 1) \), normal to the vertical wall with the linear temperature and concentration variations with uniform injection/suction rate(fig.1e).

### 6.2 Analysis

Consider mixed convection from a permeable plate inclined at angle \( m\pi/2 \) with respect to the horizontal direction with surface injection and suction at a velocity \( v_w(x) \), where \( x \) and \( y \) are the cartesian co-ordinates in the directions along and perpendicular to inclined surface under consideration. We shall assume that (1) the properties of the fluid and porous medium are homogeneous and isotropic, (2) the convective fluid and porous medium are everywhere in thermodynamic equilibrium, (3) the Boussinesq approximation is invoked and (4) the temperature is everywhere below boiling point. The equations governing the steady state conservation of mass, momentum, energy and concentration for Darcy flow through a porous medium are

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (6.1)
\]

\[
u = -\frac{K}{\mu} \left( \frac{\partial p}{\partial x} \pm \rho g x \right) \quad (6.2)
\]

\[
v = -\frac{K}{\mu} \left( \frac{\partial p}{\partial y} \pm \rho g y \right) \quad (6.3)
\]

\[
\frac{\partial T}{\partial x} + \nu \frac{\partial^2 T}{\partial y^2} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (6.4)
\]

\[
u \frac{\partial C}{\partial x} + \nu \frac{\partial C}{\partial y} = D \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) \quad (6.5)
\]

\[
\rho = \rho_\infty \left[ 1 - \beta_t (T - T_\infty) - \beta_c (C - C_\infty) \right] \quad (6.6)
\]
where \( u, v, p, \rho, \nu, g, K, \alpha, D \) are the volume averaged velocity components, pressure, solution density, kinematic viscosity of the fluid, acceleration due to gravity, permeability, thermal and concentration diffusivities of the porous medium respectively. \( T \) and \( C \) denote the temperature and concentration inside the boundary layers. If \( Tw > T_\infty \), then, when the flow is vertically upward we have the aiding case and so required the upper sign in the equations (6.2) and (6.3) and for the co-ordinate system shown in figs. 1(a) and 1(b) and where as flow is vertically downward we have the opposing case and the lower sign is required and denote the system shown in figs. 1(c) and 1(d). This situation is reversed if \( Tw < T_\infty \). \( g_x = g \cos m \pi /2 \) and \( g_y = g \sin m \pi /2 \) are the components of gravitational acceleration vectors along the \( x \) and \( y \) directions. The subscript "\( \infty \)" in equation (6.6) denotes the condition at infinity.

The boundary conditions for the problem are:
\[
\begin{align*}
\text{at } y = 0, & \quad T_w = T_\infty \pm Ax^\lambda, C_w = C_\infty \pm dx^\gamma, \nu = ax^n \\
\text{at } y = \infty, & \quad T = T_\infty, C = C_\infty, u = U_\infty(x) = Bx^l
\end{align*}
\] 

(6.7)

where \( A > 0 \), \( B > 0 \) and \( d > 0 \). It is clear that \( a \) is positive for injection of fluid and negative for withdrawal of fluid. For the mixed convection we will designate as aiding flows where buoyancy force has a component in direction of free stream velocity i.e \( T_w = T_\infty + Ax^\lambda, C_w = C_\infty + dx^\gamma \) in the figs. 1(a) and 1(b) or \( T_w = T_\infty - Ax^\lambda, C_w = C_\infty - dx^\gamma \) in figs. 1(c) and 1(d). While we will designate as opposing flows when the buoyancy force has a component opposite to the free stream velocity such as \( T_w = T_\infty - Ax^\lambda \) and \( C_w = C_\infty - dx^\gamma \) in figs. 1(a) and 1(b) or \( T_w = T_\infty + Ax^\lambda \) and \( C_w = C_\infty + dx^\gamma \) in figs. 1(c) and 1(d).

By potential theory, the velocity in the \( x \)-direction along the inclined surface for the co-ordinate shown in the fig.1 is given by

\[ u = U_\infty(x) = Bx^l \]

where \( B > 0 \) and \( m \), \( l \) are related by \( m = 2l/(l+1) \)

If we introduce the stream function such as \( u = \frac{\partial \psi}{\partial y} \) and \( v = -\frac{\partial \psi}{\partial x} \), the governing equations
from (6.1) to (6.6) in terms of $\psi$, $T$ and $C$ are

\[
\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = \pm \frac{K}{\nu} (\beta_t (g_x \frac{\partial T}{\partial y} - g_y \frac{\partial T}{\partial x}) + \beta_c (g_x \frac{\partial C}{\partial y} - g_y \frac{\partial C}{\partial x}))
\]

(6.8)

\[
\frac{\partial \psi}{\partial y} \frac{\partial T}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial T}{\partial y} = \alpha (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2})
\]

(6.9)

\[
\frac{\partial \psi}{\partial y} \frac{\partial C}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial C}{\partial y} = D (\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2})
\]

(6.10)

For horizontal boundary layers where $g_z = 0$, above approximation is valid for wide range of inclined angles except for $m = 0$ in figs. 1(a) and 1(c) or $m = 1$ in figs. 1(b) and 1(d). Experimental and numerical studies on convective heat and mass transfer in a porous medium show that thermal and concentration boundary layers exist adjacent to the heated or cooled walls. When the thermal boundary layer is thin, boundary layer approximations analogous to classical boundary layer theory can be applied. Near the boundary, the normal component of seepage velocity is small compared with the other component of the seepage velocity and the derivatives of any quantity in the normal direction are large compared with derivatives of the quantity in the direction of the wall. Under these assumptions, the above equations become

\[
\frac{\partial^2 \psi}{\partial y^2} = \pm \frac{K g_x}{\nu} (\beta_t \frac{\partial T}{\partial y} + \beta_c \frac{\partial C}{\partial y})
\]

(6.11)

\[
\frac{\partial \psi}{\partial y} \frac{\partial T}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2}
\]

(6.12)

\[
\frac{\partial \psi}{\partial y} \frac{\partial C}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2}
\]

(6.13)

where $g_x$ and $g_y$ are of the same order of magnitude and positive and negative signs correspond to figs. 1(a),1(b) and figs. 1(c),1(d) respectively.

To search the similarity solution for the above boundary layer equations (6.10) to (6.12) with boundary conditions, we are taking the following nondimensional similarity transformations

\[
\psi = (\alpha U_{\infty} x)^{1/2} f(\eta)
\]

(6.14)
\[ \eta = \frac{y}{x}(U_\infty x/\alpha)^{1/2} \]  
\hspace{1cm} (6.15)

\[ \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty} \]  
\hspace{1cm} (6.16)

\[ \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \]  
\hspace{1cm} (6.17)

In terms of new transformations, it is easy to prove that the components of velocity in \( x \) and \( y \) directions are

\[ u = U_\infty(x)f'(\eta) \]  
\hspace{1cm} (6.18)

\[ v = \frac{1}{2}(\alpha U_\infty(x)/x)^{1/2}[(1 - l)\eta f' - (1 + l)f] \]  
\hspace{1cm} (6.19)

Using above transformations and velocity vectors, the governing equations (6.11) to (6.13) become

\[ f'' = \left( \pm K g_{xg}/\nu B \right) x^{(x-l)}(\theta' + \frac{d\beta x^{(x-l)}(\gamma - \lambda)}{\beta x A} \phi' \right) \]  
\hspace{1cm} (6.20)

\[ \theta'' = \lambda \theta f' - \frac{(1 + n)}{2} f \theta' \]  
\hspace{1cm} (6.21)

\[ \phi'' = \gamma \phi f' - \frac{(1 + n)}{2} f \phi' \]  
\hspace{1cm} (6.22)

The boundary conditions now become

\[ \eta = 0, \hspace{0.5cm} f = f_w, \hspace{0.2cm} \theta = 1, \phi = 1 \]  
\hspace{1cm} (6.23)

\[ \eta \to \infty, \hspace{0.2cm} f' \to 1, \theta = 0, \phi = 0 \]  
\hspace{1cm} (6.23)

where \( f_w(x) \) is lateral mass flux parameter

\[ f_w = \frac{-2ax^{n+1/2 - 1/2}}{(\alpha B)^{1/2}(1 + l)} \]  
\hspace{1cm} (6.24)

Similarity will exist when the terms in equations (6.19) to (6.22) will free from \( x \) so it is obvious now \( l = \lambda = \gamma \), \( n = (l - 1)/2 \). Under such conditions, above equations become

\[ f'' = Gr(\theta' + N\phi') \]  
\hspace{1cm} (6.25)
\[ \theta'' = \lambda \theta' - \frac{(1 + \lambda)}{2} f \theta' \]  
\[ \phi'' = \lambda \phi' - \frac{(1 + \lambda)}{2} f \phi' \]  
\[ f_w = \frac{-2a}{(\alpha B)^{1/2}(1 + \lambda)} \]  

where \( Gr = \pm Kg_x \beta \theta \omega / \mu U_\infty \) is modified Grashof number and \( N = \beta_c \phi \omega / \beta \theta \omega \) is Bouyancy ratio.

Equation (6.25) can be integrated with boundary conditions at \( y = \infty \), now the governing equation becomes

\[ f' = Gr[\theta + N\phi] + 1 \]  

with \( l = \lambda \), free stream velocity is \( U_\infty(x) = Bx^\lambda \), where \( m = 2\lambda/(1 + \lambda) \).

Equations (6.25) to (6.28) with boundary conditions are nonlinear system of equations which has to be solved for the problem of combined heat and mass transfer mixed convection about a plate inclined with the horizontal direction at an angle \( m\pi/2 \).

For the special case of \( Gr = 0 \), equation (6.20) to (6.24) show that similarity solutions are possible for arbitrary values of \( \lambda, \gamma \), and \( n \). For limiting case equation (6.20) can be integrated to give \( f' = 1 \) and \( f = \eta \) with use of boundary conditions, substituting this in above equations we have

\[ f = \eta + f_w \]  
\[ \theta'' = - \frac{(\lambda + 1)}{2} f \theta' + \lambda \theta \]  
\[ \phi'' = - \frac{(\lambda + 1)}{2} f \phi' + \lambda \phi \]  

which with the boundary conditions can be integrated numerically.

The equations (6.25) to (6.28) with boundary conditions are solved numerically for discrete sequences of \( (N, Gr), (Le, Gr), (Le, f_w), (N, f_w), \) and \( (f_w, Gr) \) pairs. The numer-
6.3 Results and Discussions

In this section the only results presented will be from the solutions of equations (6.23) to (6.26) for the entire mixed convection regime under the conditions of buoyancy assisting and opposing flows. Integrations have been carried out for the following cases (a) $\lambda = 1 = 0$, $n = -1/2$ (b) $\lambda = l = 1/3$, $n = -1/3$ (c) $\lambda = l = 1$, $n = 0$ which corresponds to mixed convection from (a) an isothermal vertical flat plate with the injection or withdrawal rate varying with $x^{-1/2}$, (b) corresponds to a free stream flowing over an inclined wall ($m = 45^\circ$) having constant heat flux with injection or withdrawal rate varying with $x^{-1/3}$ and (c) corresponds to a stagnation flow normal to a vertical wall with linear temperature and concentration variations with constant injection/withdrawal rate (fig.1e).

The physical characteristics of importance are rates of heat and mass transfer which are computed from the wall to the medium with help of the following definitions

$$q = -k \frac{\partial T}{\partial y} = \left( (k\theta_{w}/x)Ra_{x}^{1/2}(-\theta' (0)) \right)_{nc}$$  \hspace{1cm} (6.33)

$$= \left( (k\theta_{w}/x)Pe_{x}^{1/2}(-\theta' (0)) \right)_{mc}$$  \hspace{1cm} (6.34)

$$m = -D \frac{\partial C}{\partial y} = \left( (D\phi_{w}/x)Ra_{x}^{1/2}(-\phi' (0)) \right)_{nc}$$  \hspace{1cm} (6.35)

$$= \left( (D\phi_{w}/x)Pe_{x}^{1/2}(-\phi' (0)) \right)_{mc}$$  \hspace{1cm} (6.36)

The heat transfer coefficient in terms of Nusselt number is given by

$$Nu = \frac{qx}{k(T_{w} - T_{\infty})} = Ra_{x}^{1/2}(-\theta' (0))_{nc}$$  \hspace{1cm} (6.37)

$$= Pe_{x}^{1/2}(-\theta' (0))_{mc}$$  \hspace{1cm} (6.38)
while the mass transfer coefficient in terms of Sherwood number is given by

\[ Sh = \frac{m_x}{D(C_w - C_{\infty})} = Ra_x^{1/2}(-\phi'(0))_{nc} \]  

(6.39)

\[ = Pe_x^{1/2}(-\phi'(0))_{mc} \]  

(6.40)

where \( Ra_x = Kg\beta_\theta_{x}\nu/\alpha \nu \), \( Pe_x = U_{\infty}x/\alpha \) are modified Rayleigh and Peclet numbers respectively. \( k \), \( q \), \( m \) are effective thermal conductivity, local heat and mass fluxes respectively. The values of \( Nu/Pe_x^{1/2} \), \( Sh/Pe_x^{1/2} \) are computed for various values of Grashof number, buoyancy ratio and Lewis number with considerable effect of lateral mass flux. The results are presented through tables and graphs. To check the accuracy of present solutions, the Nusselt number for aiding and opposing cases are compared with Cheng[6] for \( N = 0 \) in tables 1(a) and 1(b). It is obtained that the results are exactly same.

To understand the effects of various parameters on the mixed convection process in the present analysis Grashof number is varied from 0 to 50, Lewis number 1 to 100 and buoyancy ratio -1 to 3 and mass flux parameter -1 to 1 where \( f_w = 0 \) corresponds to the impermeable surface, \( f_w > 0 \) corresponds to suction and \( f_w < 0 \) for injection of the fluid into the porous medium. Figures 2 to 9 show that how the thermal and concentration boundary layers react to change with the above parameters.

**AIDING CASE:**

Fig. (2) corresponds to Nusselt or Sherwood numbers with respect to buoyancy ratio for fixed Lewis and Grashof numbers \((Le = 1, Gr = 10)\) for various values of \( \lambda = 0, 1/3, 1 \). Figure shows rate of heat or mass transfer increases with buoyancy ratio. From this figure it is apparent that injection decreases the Nusselt and Sherwood numbers while suction increases them. It is true for vertical surface as well as for inclined one. It is evident from figure that above result is for stagnation flow also. From fig.3 it is predicted that for fixed buoyancy ratio and Grashof number \((N = 1, Gr = 10 and Le = 2)\), the coefficient
of heat transfer decreases for injection and increases for suction. But it is observed that Nusselt number is less for vertical wall as compared to inclined and stagnation flow. Fig.4 also predicts same trend of results while it is against Sherwood number. Fig.5 is plotted for Lewis number vs Nusselt number. Figure shows rate of heat transfer decreases with Lewis number and it is also decreases from suction to injection domain for fixed values of N and Gr(N = 1, Gr = 10) for all types of flows. Fig. 6 shows Sherwood number increases with Lewis number and it also increases from injection to suction domain for fixed N and Gr(N = 1, Gr = 10) for all types of flows.

**OPPOSING CASE:**

Fig. (7) corresponds to Nusselt or Sherwood numbers for fixed Grashof and Lewis numbers (Gr = .2, Le = 1) which shows that rate of heat or mass transfer is decreased for suction and injection both for all kind of flows. It is decreased with buoyancy ratio. Where fig.(8) shows increment of Nusselt number with mass flux parameter for all values of λ and for fixed N, Gr and Le (N = 1, Gr = .1 and Le = 2). Fig. (9) depicts that Sherwood number is increased with suction parameter for all λ and fixed N, Gr and Le.
Bibliography


Table 1(a). Nusselt and Sherwood numbers (\( \text{Nu/Pe}^{1/2} \) or \( \text{Sh/Pe}^{1/2} \) for \( \text{Gr} = 1 \), \( \text{Le} = 1 \) for aiding flows.

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Table 1(b). Nusselt and Sherwood Numbers For $Le = 1$ and $Gr = .2$
For Opposing Case.

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Fig. 1 The regime in which the phenomenon of mixed convection heat and mass transfer for different angles exist.
Fig. 2 Heat or Mass Transfer Coefficient as a Function of buoyancy ratio for aiding case.
Fig. 3 Heat Transfer Coefficient as a Function of mass flux parameter for Aiding case.
Fig.4 Mass Transfer Coefficient as a Function of mass flux parameter for Aiding Case.
**Fig. 5** Heat Transfer Coefficient as a function of Lewis number for Aiding case.
Fig. 6 Mass Transfer Coefficient as a function Lewis number for Aiding case.
Fig. 7 Heat or Mass Transfer Coefficient as a Function of buoyancy ratio for Opposing case.
Figure 8. Heat Transfer Coefficient as a Function of mass flux parameter for Opposing Case.
**Fig. 9:** Mass Transfer Coefficient as a Function of mass flux parameter for Opposing Case.