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Research Paper

FINITE ELEMENT ANALYSIS OF FULLY DEVELOPED MIXED CONVECTION THROUGH A VERTICAL CHANNEL IN THE PRESENCE OF HEAT GENERATION/ABSORPTION WITH FIRST ORDER CHEMICAL REACTION

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Fully developed Mixed Convection through vertical channel in the presence of heat generation/absorption with first order chemical reaction is analyzed. The thermal boundary conditions are isothermal-isothermal for left and right walls of the channel and kept at different temperatures. The effect of thermal buoyancy parameter, concentration buoyancy parameter and heat generation/absorption parameter are studied. Also the flow field with the presence of first order chemical reaction is particularly analyzed. The governing equations are solved using finite element method. Velocity, temperature and concentration profiles are investigated for different values of the flow parameters.

Keywords: Mixed convection, Laminar flow, Vertical channel, Chemical reaction, Finite element method

INTRODUCTION

In convective heat transfer combined free and forced convection (Mixed convection) is vital as it has most prominent applications in the field of Science and Engineering. Mixed convection occur when both free and forced convection have significant effect on heat transfer. In this, both buoyancy and pressure forces interact. It depends on many factors like, flow, temperature, geometry and orientations. The fluid nature is also of significance, as Grashof constant increases in a fluid as temperature increases which cause the change in flow. There is an enhanced interest in flow through vertical channels among the researchers. The common cases are on heating or cooling of channel walls, and at the small velocities of fluid flow that are characteristic of laminar flow, mixed convection is realized. Forced convection (Laminar) may be obtained in capillaries. Channel flows have been studied substantially since 1960 after their increased importance in the various fields of science and

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engineering. Mixed convection is normally observed in high-powered-output devices, like Nuclear reactor technology, electronic cooling, etc. In electronic cooling, the components are assembled on the circuit card, an array of which is placed vertically so that forming the vertical channel through this a coolant is passed. Also mixed convection has applications in solar systems, heat exchangers and chemical industries.

Literature survey reveals that lot of papers are available in this area, Win Aung and Worku (1986) have basically analyzed the theory of fully developed, combined convection including the flow reversal, the numerical simulation of forced convective incompressible flow in a channel an array of heated obstacles attached to one was studied by Timothy and Kambiz Vafai (1998), papers by Aung and Worku (1986) and Habachi and Acharya (1986) have given ideas about fluid flow and thermal characteristics inside a vertical channel with symmetrical or asymmetrical thermal boundary conditions. Cheng *et al.* (1990) has concentrated on the analysis of flow reversal and heat transfer of fully developed mixed convection in vertical channel, Hamdah and Wirtz (1991), Berletta (1998 and 2002) pointed out the relevant effects of laminar mixed convection in a vertical channel and flow reversal in vertical duct with uniform heat fluxes. Gill and Casal (1962) showed that the buoyancy significantly affects the flow of low prandtl number fluids which is highly sensitive to gravitational force and the extent to which the buoyancy force influences a forced flow. A Berletta (1999) has worked on the fully developed mixed convection and flow reversal of power law fluid in vertical channel. A Berletta (2001) has analyzed the flow reversal for laminar and mixed convection in vertical duct with one or more isothermal walls for the fully developed flow.

Flow of fluid with internal heat generation/ absorption is of great experimental as well as theoretical importance. The volumetric heat generation/absorption term exerts strong effect on the heat transfer and flow when the temperature difference is significantly high. This analysis is of much importance in view of chemical reaction concerned with disassociating fluids. Combined natural and forced convection in vertical channels is commonly arises in nuclear reactor applications, particularly when dealing with the after shut down cooling problems. Md. Mamun Molla *et al.* (2004) have investigated the effect of internal heat generation/absorption on a steady two dimensional natural convection flow of viscous incompressible fluid alone uniformly heated vertical wavy surface. Acharya *et al.* (2003) analyzed the flow problems in the presence of heat generation. Umavathi *et al.* (2013) discussed the laminar magneto convection flow in a vertical channel in the presence of heat generation or absorption.

The increased scope for chemical reaction in chemical and hydrometallurgical industries, the study of heat transfer with chemical reaction has become the need of the hour. There are many transport processes governed by the combined action of buoyancy forces due to both thermal and mass diffusion in the presence of chemical reaction effects. These are commonly encountered in nuclear safety and combustion systems, solar collectors, metallurgical and chemical engineering. Also the other applications include binary alloys and crystal growth dispersion of dissolved materials of particulate water in flows, drying and dehydration operations in chemical of atomized liquids. Anjalidevi and Kandaswamy

(1999) investigated the effect of chemical reaction and heat and mass transfer on laminar flow along a semi infinite horizontal plate. Fully developed laminar mixed convection flow in a vertical channel in the presence of first order chemical reactions has been studied by Prathap Kumar *et al.* (2013). An analytical solution of dispersion of solute with first order chemical reaction in a vertical double passage channel filled with porous medium has been analyzed by Prathap Kumar *et al.* (2014), Muthucumaraswamy and Ganesan (2001) have investigated the impulsive motion of a vertical plate with heat flux/mass, flux/suction and diffusion of chemically reactive species. Seddeek (2005) has used the finite element method for studying the effect of chemical reaction, variable viscosity, thermophoresis and heat generation/absorption on a boundary layer hydro magnetic flow with heat and mass transfer over a heat surface. Prathap Kumar *et al.* (2012) considered the homogeneous and heterogeneous chemical reactions in immiscible fluids. Muthucumaraswamy and Ganesan (2001), have investigated the first order chemical reaction on flow past an impulsively started vertival plate with uniform heat and mass flux. Prasad *et al.* (2017) studied mixed convective fully developed flow in a vertical channel in the presence of thermal radiation and viscous dissipation. Umavathi *et al.* (2013) have worked on, laminar Magneto Convection flow in a Vertical channel in the presence of heat generation and absorption.

In view of this the Finite Element analysis of fully developed Mixed Convection through vertical channel in the presence of heat generation/absorption with first order chemical reaction has not been considered yet in literature. The aim of this study is to investigate the fully developed mixed convection through vertical channel in the presence of heat generation/absorption with first order chemical reaction. This analysis adds very useful inputs to the existing literature.

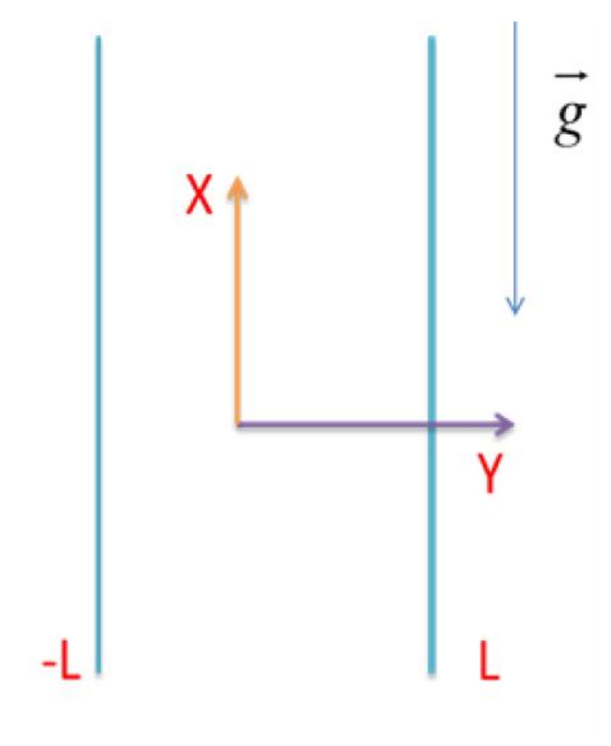
MATHEMATICAL FORMULATION

The nature of the fluid considered is laminar and Newtonian which flows steadily in a parallel plate vertical channel. It is assumed that Boussinesq approximation holds, hence the thermal conductivity, thermal diffusivity, dynamic viscosity and thermal expansion coefficients are considered constant. Equation of state under Boussinesq approximation is

$$° = °_0[1- \quad (T - T_0)] \qquad ...(1)$$

Figure 1 shows the spatial coordinate system for the fluid flow. The X-axis is parallel to the gravitational field but with opposite direction and Y-axis is parallel to the horizontal direction.

Figure 1: Physical Configuration



For fully developed flow, the only nonzero component of velocity is the X component, thus equation of continuity equation is obtained as

$$\frac{\partial U}{\partial X} = 0 \qquad ...(2)$$

That is U depends only Y.

Also the X-momentum, Y-momentum, energy (neglecting viscous dissipation) and concentration equations are as given below

$$g\ _T(T - T_0) + g\ _C(C - C_0) - \frac{1}{°_0}\frac{dP}{dX} + ¬\frac{d^2U}{dY^2} = 0 \qquad ...(3)$$

$$\frac{\partial P}{\partial Y} = 0 \qquad ...(4)$$

$$\frac{d^2T}{dY^2} \pm \frac{Q(T - T_0)}{K} = 0 \qquad ...(5)$$

$$D\frac{d^2C}{dY^2} - KC = 0 \qquad ...(6)$$

From (2) U will only be a function of the horizontal distance Y and also for the temperature boundary conditions, a constant pressure gradient ($\frac{dP}{dX}$) is required for the compatibility.

Boundary Conditions

Velocity, temperature and concentration

$$U(-L) = U(L) = 0$$

$$at\,Y = -L \quad T = T_1\ , \quad C = C_1$$

$$at\,Y = L \quad T = T_2\ , \quad C = C_2 \qquad ...(7)$$

It is assumed that $T_2 \geq T_1$ and $C_2 \geq C_1$

Above dimensional equations are expressed in non-dimensional form using the following variables

$$u = \frac{U}{U_0},\ y = \frac{Y}{H},\ \ ^- = \frac{T - T_0}{T_1 - T_2} = \frac{T - T_0}{\Delta T},$$

$$¤ = \frac{C - C_0}{C_2 - C_1} = \frac{C - C_0}{\Delta C},\ Gr_T = \frac{g\ _T \Delta T H^3}{¬^2},$$

$$Gr_C = \frac{g\ _C \Delta C H^3}{¬^2},\ \mathrm{Re} = \frac{U_0 H}{¬^2},$$

$$a_T = \frac{Gr_T}{\mathrm{Re}},\ a_C = \frac{Gr_C}{\mathrm{Re}},\ p = -\frac{H^2}{«U_0}\frac{dP}{dX},$$

$$\Delta T = T_2 - T_1\ \ \Delta C = C_2 - C_1,$$

$$T_0 = \frac{T_1 + T_2}{2},\ C_0 = C_1 \qquad ...(8)$$

Thus, non-dimensional equations for momentum, temperature and concentration are

$$\frac{d^2u}{dy^2} + a_T\,^- + a_C¤ + p = 0 \qquad ...(9)$$

$$\frac{d^{2-}}{dy^2} \pm \cdot\ ^- = 0 \qquad ...(10)$$

$$\frac{d^2¤}{dy^2} - \sim^2¤ = 0 \qquad ...(11)$$

where $\cdot = \frac{QH^2}{K}$, $\sim^2 = \frac{KH^2}{D}$

Non-dimensional boundary conditions are

At $Y = -L\ ,\quad y = -\frac{1}{2},\ \ ^- = -\frac{1}{2},\ ¤ = 0$

$$Y = L\ ,\quad y = \frac{1}{2},\ \ ^- = \frac{1}{2},\quad ¤ = 1 \qquad ...(12)$$

SOLUTIONS

The governing equations are solved using Finite element method. The effects of thermal buoyancy

a_T and concentration buoyancy a_C, heat generation/absorption parameter $\cdot$, concentration parameter ¤ are all investigated. Velocity, temperature, concentration profiles are presented graphically and interpreted.

The dimensionless Equations (9) to (11) with boundary conditions (12) are solved using Finite element method. It is a numerical tool for determining solutions to a large class of engineering problems. Now a day, this method has gained a considerable attention of researchers, because of its diversity and flexibility as an analysis tool. The method has been considered because of its accuracy in its results compare to other methods. Also the results have been compared with analytical solution and found to be in good agreement.

The normal procedure in Finite element method involves mainly:

- Discretization of the domain in to flexible elements
- Select interpolation or Shape function
- Formation of element equations
- Assembling the element equations to obtain a system of simultaneous equations
- Solve the system of equations.

Finite Element Procedure

Applying the Galerkin method to solve the governing differential Equations (9) to (11) on a specified region 0 < y< l gives

$$\int_0^l \left[\frac{d^2\tilde{u}}{dy^2} + a_T \tilde{-} + a_C \tilde{\text{¤}} + p \right] N_i dy = 0 \qquad ...(13)$$

$$\int_0^l \left[\frac{d^2\tilde{-}}{dy^2} \pm \cdot \tilde{-} \right] N_i dy = 0 \qquad ...(14)$$

$$\int_0^l \left[\frac{d^2\tilde{\text{¤}}}{dy^2} - \sim^2 \tilde{\text{¤}} \right] N_i dy = 0 \qquad ...(15)$$

Now carrying out integration by parts for (13), (14), (15) we get:

$$\left[N_i \frac{d\tilde{u}}{dy} \right]_0^l - \int_0^l \frac{d\tilde{u}}{dy}\frac{dN_i}{dy} dy + a_T \int_0^l N_i \left[N_i \bar{-}_i + N_j \bar{-}_j \right] + a_C \int_0^l N_i \left[N_i \text{¤}_i + N_j \text{¤}_j \right] + p \int_0^l N_i \, dy = 0$$

$$\left[N_i \frac{d\tilde{-}}{dy} \right]_0^l - \int_0^l \frac{d\tilde{-}}{dy}\frac{dN_i}{dy} dy \pm \cdot \int_0^l N_i \left[N_i \bar{-}_i + N_j \bar{-}_j \right] dy = 0$$

$$\left[N_i \frac{d\tilde{\text{¤}}}{dy} \right]_0^l - \int_0^l \frac{d\tilde{\text{¤}}}{dy}\frac{dN_i}{dy} dy - \sim^2 \int_0^l N_i \left[N_i \text{¤}_i + N_j \text{¤}_j \right] dy = 0$$

Linear element is given by

$$\tilde{u} = N_i u_i + N_j u_j$$

$$\tilde{-} = N_i \bar{-}_i + N_j \bar{-}_j \quad \tilde{\text{¤}} = N_i \text{¤}_i + N_j \text{¤}_j$$

$$N_i = \frac{y_j - y}{y_j - y_i}, \; N_j = \frac{y - y_i}{y_j - y_i}$$

To evaluate the above integrals we use the formula $\int N_i^a \, N_j^b dl = \frac{a!b!}{(a+b+1)!} l$

By element properties, we assemble element stiffness matrix and nodal force vector of the element. The element stiffness and load matrix is

$$[K][T] = [F] \qquad ...(16)$$

where,

$$[K] = \begin{pmatrix} -\frac{1}{l} & \frac{a_T l}{3} & \frac{a_C l}{3} & \frac{1}{l} & \frac{a_T l}{6} & \frac{a_C l}{6} \\ 0 & \frac{\cdot l}{3} - \frac{1}{l} & 0 & 0 & \frac{\cdot l}{6} + \frac{1}{l} & 0 \\ 0 & 0 & -\frac{1}{l} - \frac{\sim^2 l}{3} & 0 & 0 & \frac{1}{l} - \frac{\sim^2 l}{6} \\ \frac{1}{l} & \frac{a_T l}{6} & \frac{a_C l}{6} & -\frac{1}{l} & \frac{a_T l}{3} & \frac{a_C l}{3} \\ 0 & \frac{\cdot l}{6} + \frac{1}{l} & 0 & 0 & \frac{\cdot l}{3} - \frac{1}{l} & 0 \\ 0 & 0 & \frac{1}{l} - \frac{\sim^2 l}{6} & 0 & 0 & -\frac{1}{l} - \frac{\sim^2 l}{3} \end{pmatrix}$$

$$[T]=\begin{pmatrix} u_i \\ -_i \\ \Phi_i \\ u_j \\ -_j \\ \Phi_j \end{pmatrix} \quad [F]=\begin{pmatrix} -\frac{Pl}{2} \\ 0 \\ 0 \\ -\frac{Pl}{2} \\ 0 \\ 0 \end{pmatrix}$$

$$l = Y_j - Y_i$$

Equation (16) is solved with the boundary conditions (12) using a MATLAB program to get the profiles for velocity, temperature and concentration.

RESULTS AND DISCUSSION

Fully developed mixed convection through a vertical channel in the presence of heat generation/ absorption with first order chemical reaction is studied using Finite element method. The velocity, temperature and concentration profiles are presented graphically and interpreted. The effect of ª$_T$, ª$_C$, · and ~, on velocity, temperature and concentration are analyzed.

Figure 2, illustrates that for different values of ª$_T$ there is a significant change in the velocity profile. For ª$_T$ = 0 the Poiseulle parabolic profile is obtained. With increase in the values of ª$_T$ increases the buoyancy force inducing natural convection, hence the flow accelerates near the hot wall (more and more channeled towards the hot wall). For further higher values, the flow reversal that is the back flow is observed near the cooler wall, because, increased buoyancy force moves the hot fluid up and the cold down (free convection dominates). Fluid velocities are larger adjacent to the hot wall. In this case the parameters except thermal Grashof constant are

Figure 2: Velocity Profiles for Different Values of ª$_T$

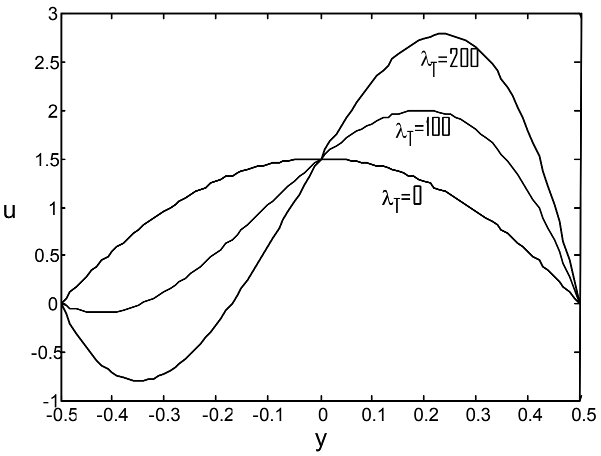
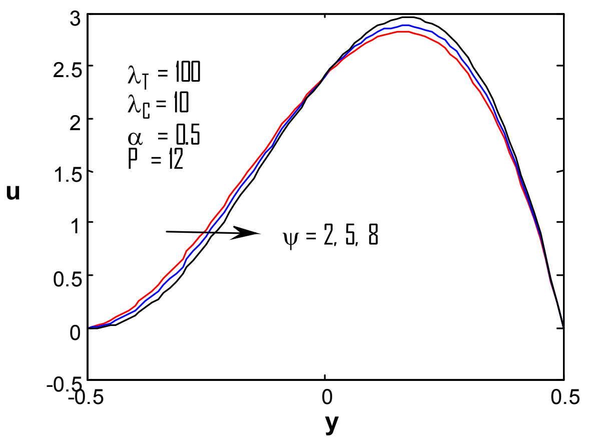


Figure 3: Velocity Profiles for Different Values of Heat Generation Parameter ·



equal to zero, ª$_C$ = 0, · = 0, ~ = 0. Also, this case is correlated with analytical solution and there is an exact match for both the methods. Velocity profiles for different values intersect at y = 0.

Figures 3 and 4 reveal the effect of on velocity profile where ª$_T$ = 100, ª$_C$ = 10, ~ = 0.5, P = 12. It is observed that increase in the values of heat generation parameter the velocity profile has a slight decrease in the flow field and intersects at y = 0 and converging at the hotter wall, where as in case of heat absorption there is a slight increase in the profile.

Figure 4: Velocity Profiles for Different Values of Heat Absorption Parameter ·

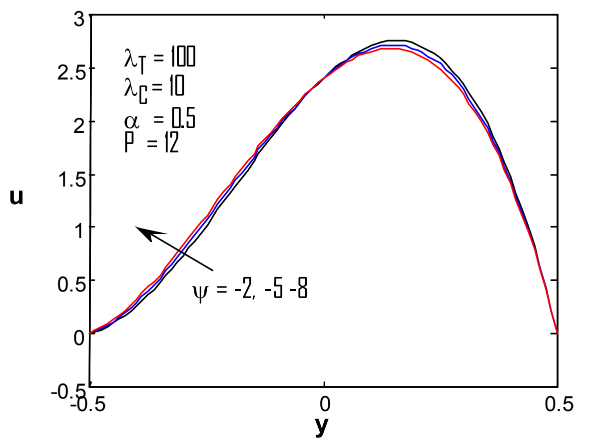


Figure 5: Velocity Profiles for Different Values of $^{a}{}_{C}$

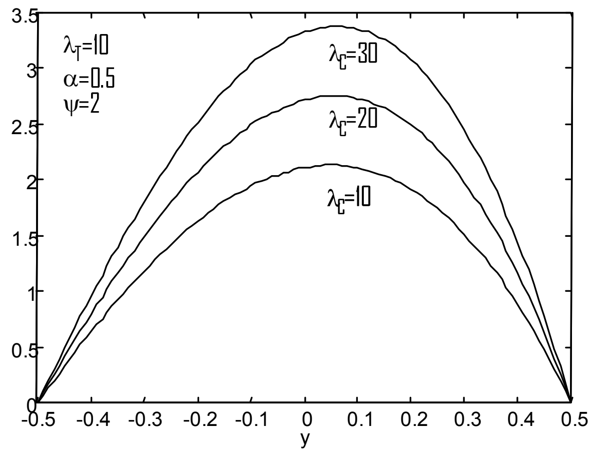


Figure 6: Velocity Profiles for Different Values of ~

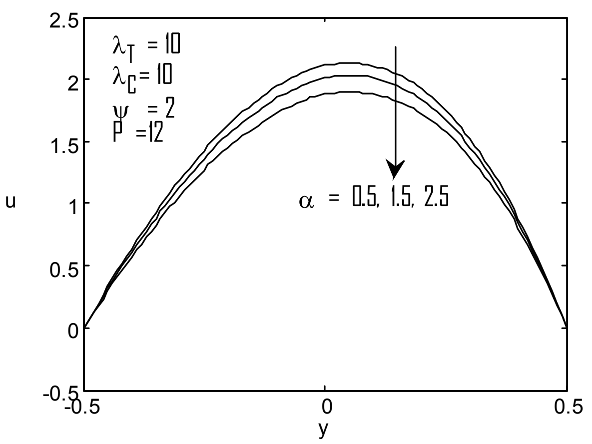


Figure 7: Velocity Profiles for Different Values of P

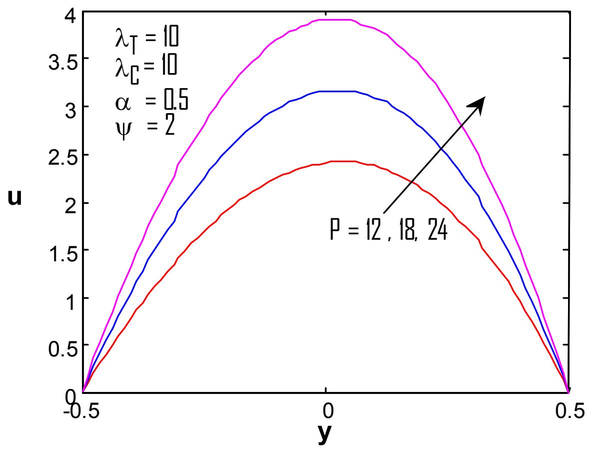


Figure 5 elucidates the effect of $^{a}{}_{C}$ on the velocity profile, where the values of the other parameters are $^{a}{}_{T}$ = 10, ~ = 0.5, P = 12. Increase in the values of $^{a}{}_{C}$, the flow field increases. The concentration buoyancy is the ratio of species buoyancy force to the viscous force, therefore increase in its values increase the buoyancy forces of the species which results in the increase in the velocity range.

A first order reaction depends on the concentration of only one reactant (a unimolecular reaction). Other reactants may be present, but each will be of order zero. The first order chemical reaction parameter ~ has significant effect on velocity profile which is interpreted in Figure 6. Increase in the value of á decrease the flow field. The effect is observed due to the increase the concentration of the reactant, in which the number of molecules per unit volume is increased, thus the collision frequency is augmented which results in decrease of velocity flow field.

The role of P on the velocity profile is shown in the Figure 7. It reveals that increase in the value of P increases the flow field.

Figure 8: Temperature Profiles for Different Values of Heat Generation Parameter ·

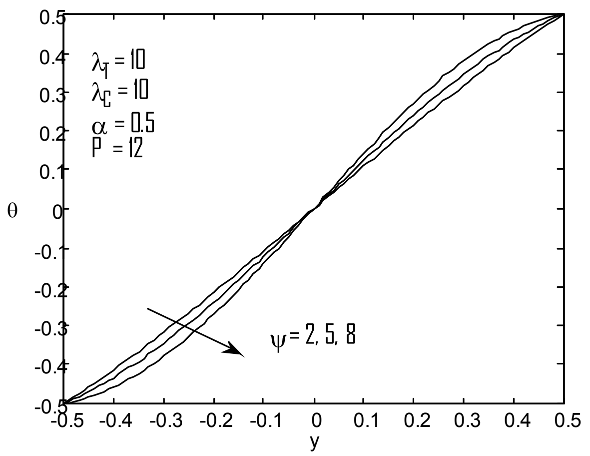
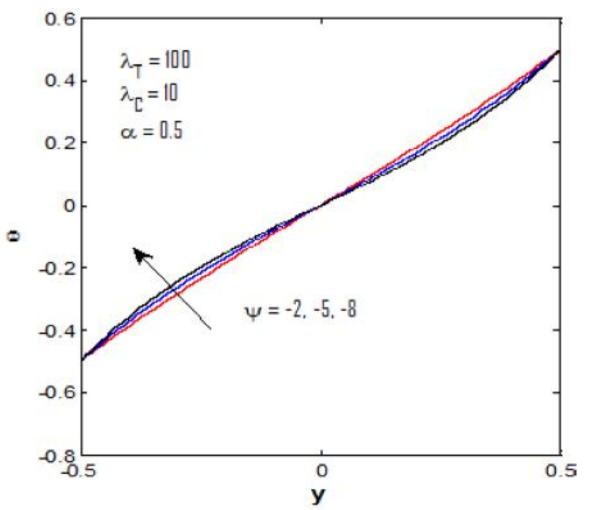


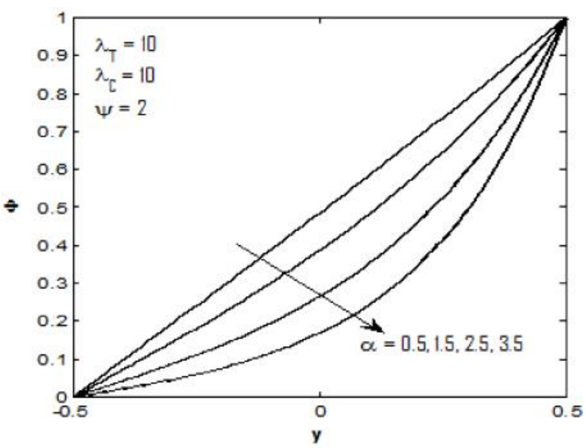
Figure 9: Temperature Profiles for Different Values of Heat Absorption Parameter ·



The effect of · on the temperature is investigated and presented in Figures 8 and 9. In case of heat generation, temperature is nearly linear for lower values and for increase in its value, the profile is nonlinear.

Profile of concentration on the basis of first order chemical reaction parameter ~ is analyzed in the Figure 10. For ~ = 0.5 the concentration profile is nearly linear and increase in its value shows a decrease in its range.

Figure 10: Concentration Profiles for Different Values ~



CONCLUSION

The problem of fully developed mixed convection through a vertical channel in the presence of heat generation/absorption with first order chemical reaction is analyzed by finite element method and following conclusions are drawn.

- Increase in thermal buoyancy, increases the velocity field with flow reversal.
- The increase in concentration buoyancy also enhances the velocity flow field.
- Heat generation/absorption parameter also increases the velocity flow field.
- Increase in Concentration parameter decreases the flow field.

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APPENDIX

Nomenclature	
U → Dimensional velocity along the X-axis	U_0 → Reference velocity
u → Dimensionless velocity along X-axis	H → Hydraulic diameter
Re → Reynolds number	« → Dynamic viscosity
Gr_T → Thermal grashof constant	Gr_C → Concentration Grashof constant
$°_0$ → Fluid density	C_0 → Reference concentration
T_0 → Reference Temperature	T_1 → Temperature at left wall
T_2 → Temperature at right wall	C_1 → Concentration at left wall
C_2 → Concentration at right wall	$_T$ → Thermal expansion coefficient
$_C$ → Thermal expansion coefficient	¯ → Dimensionless temperature
¤ → Dimensionless concentration	g → Acceleration due to gravity

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