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HEAT AND MASS TRANSFER FLOW IN A CHANNEL FILLED WITH POROUS MEDIUM IN THE PRESENCE OF VARIABLE THERMAL CONDUCTIVITY

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ABSTRACT
The natural convection fluid flow on the effect of variable thermal conductivity on heat and mass transfer with chemical reaction, porosity and buoyancy force distribution is investigated. The nonlinear partial differential equations together with the boundary conditions are reduced to dimensionless form which are solved using perturbation technique. The effects of various parameters associated with flow like magnetic field M, mass Grashof number Gc, Schmidt number Sc, buoyancy force distribution R, mass buoyancy Rc, porosity Da, chemical reaction Kr, and variable thermal conductivity λ are studied with the help of graphs. It is observed that, the velocity increase with increasing Gc or M and the temperature increase with increasing R or λ and the concentration decreases with increasing Sc or Kr.

Keywords: Buoyancy distribution effect, Chemical reaction, Heat Mass Transfer, Porous medium, Variable Thermal Conductivity

INTRODUCTION
There are several transport processes in industry and in nature where buoyancy force arises from both thermal and mass diffusion which are caused by the temperature gradients and the concentration differences of dissimilar chemical species. Hence, this analysis deals with the free convection flows driven by temperature gradients and concentration differences. When the free convection occurs at high temperatures, radiation effects, variation of viscosity with temperature and variation of thermal conductivity of the fluid cannot be neglected. Nuclear power plants, missiles, gas turbines and space vehicles are examples of such engineering areas. In the area of steady flow of viscous incompressible fluid over infinite porous plates subject to variable thermal conductivity, various aspects of the problem have been investigated by many authors. To be more specific, Sibanda and Makinde (2010) examined an investigation on steady MHD flow and heat transfer through a rotating disk in porous medium in the presence of Ohmic heating and viscous dissipation. Transport processes in porous media are encountered in a broad range of scientific and engineering problems associated with fiber and granular insulation materials, packed-bed chemical reactors and transpiration cooling. The change in wall temperature causing the free convection flow could be a sudden or a periodic one, leading to a variation in the flow. The vertical free convection boundary layer flow in porous media owing to combined heat and mass transfer has been investigated by Nield (2006). Jha *et al.* (2015) demonstrated the unsteady MHD free convective Couette flow between vertical porous plates with thermal radiation. The effects of thermal buoyancy and variable thermal conductivity in a power law fluid past a vertical stretching sheet in the presence of non-uniform heat source was accomplished by Abel *et al.* (2009). Makinde and Olanrewaju (2011) investigated the unsteady mixed convection with Soret and Dufour effects past a porous plate moving through a binary mixture of chemically reaction fluid. The reduced similarity equations were then solved numerically by applying shooting iteration technique together with fourth-order Runge-Kutta integration scheme. Mohamed *et al.* (2009) explained finite element analysis of Hydromagnetic flow and heat transfer of heat generation fluid over a surface embedded in a non-Darcian porous medium in the presence of chemical reaction. The results obtained are presented graphically for velocity, temperature, and concentration profiles, as well as Sherwood number for various parameters entering into the problem. Souayeh (2022) investigated heat transfer characteristics of fractionalized Hydromagnetic fluid with chemical reaction in permeable media. The governing fluid flow equations with boundary conditions have been transformed into set of coupled ordinary differential equations with the reduced similarity transformations and solved Fourier sine with Laplace transforms. The effects of physical parameters were examined. Convection in porous media has applications in geothermal energy recovery, oil extraction, thermal energy storage and flow through filtering devices. Convective heat transfer in porous media has received considerable attention in recent years owing to its importance in various technological applications such fiber and granular insulation, electronic system cooling, cool combustors, and porous materials, regenerative heat exchanges. Makinde (2010) explained the MHD heat and mass transfer over a moving vertical plate with a convective surface boundary condition. The effect of suction/injection on unsteady Hydromagnetic convective flow of reactive viscous fluid between vertical porous plates with thermal diffusion was reviewed by Uwanta and Hamza (2014), the reduced similarity equations were then solved analytically and numerically by perturbation technique and semi-implicit finite-difference scheme. The effects of physical parameters were examined. Ajibade *et al.* (2020) investigated adomian decomposition method for steady free convective couette flow in a vertical channel with non-linear thermal radiation, dynamic viscosity and dynamic thermal conductivity effects.

The problems of steady and unsteady flows having combined heat mass transfer by free convection with and without chemical reaction have been studied extensively by different scholars. Hamza *et al.* (2015) studied the problem of unsteady/steady Hydromagnetic convective flow between two vertical walls heated symmetrically/asymmetrically in the presence of variable thermal conductivity. Their finding showed that, the fluid velocity increase with increasing variable thermal conductivity parameter and time parameter until a steady state condition is attained. Chiam (1998) presented the heat transfer in a fluid with variable thermal conductivity over a linearly stretching sheet, and the reduced similarity equations were then solved analytically and numerically by perturbation technique and shooting method. The effects of physical parameters were examined. The MHD free convective flow along flat plate with variable thermal conductivity and viscosity depending on temperature was experimented by Nasrin and Alim (2009). Due to the numerous applications of chemical reaction effect; for example, in chemical engineering, in polymer production and in manufacturing of ceramics etc. this effect is also considered in the present study. Rout *et al.* (2013) established the MHD heat and mass transfer of chemical reaction fluid flow over a moving vertical plate in presence of heat source with convective surface boundary condition. Muhim (2018) discussed effect of variable thermal conductivity and the inclined magnetic field on MHD plane Poiseuille flow in a porous channel with non-uniform plate temperature. The reduced similarity equations were then solved by finite difference technique. Sehra, *et al.* (2021) studied convection heat mass transfer and MHD flow over a vertical plate with chemical reaction, arbitrary shear stress and exponential heating. Bisht *et al.* (2011) investigated the effects of variable thermal conductivity and chemical reaction on steady mixed convection boundary layer flow with heat and mass transfer inside a cone due to a point sink, the fluid viscosity and thermal conductivity have been assumed to be temperature dependent, the governing fluid flow equations with boundary conditions have been transformed into set of coupled ordinary differential equations with the help of similarity transformations and solved Runge-Kutta method with Shooting technique; also, with increasing values of mixed convection parameter, velocity, temperature and concentration decreases and the study is relevant in conical nozzle and diffuser flow problems exist in petroleum and chemical industries. Sani and Kaita (2023) studied steady state free convection with heat and mass transfer in the presence of variable thermal conductivity. Makinde (2021) investigated a note on the Hydromagnetic Blasius flow with variable thermal conductivity. The governing fluid flow equation with boundary condition have been transformed into set of coupled ordinary differential equations with the help of similarity transformations and solved shooting method with Runge-Kutta-Fehlbery integration scheme and concluded that the wall skin friction is an increasing function of the magnetic field parameter, the heat transfer rate increases with Prandtl number and magnetic field parameter but drops with increasing values of the thermal conductivity, both thermal and velocity boundary layer thickness lessen with a rise in magnetic field parameter intensity, and the fluid temperature increases with a rise in thermal conductivity but diminishes with a rise in Prandtl number parameter. Furthermore, Saeed *et al.* (2019) discussed Heat and Mass transfer of free convection flow over a vertical plate with chemical reaction under wall slip effect. Solutions for the fluid velocity, temperature and concentration are achieved in closed forms by applying Laplace transform. Dagana and Amos (2020) investigated MHD free convection heat and mass transfer flow in a porous medium with Dufour and chemical reaction effects. The aim of the present work is motivated to study steady state free convection with heat and mass transfer in the presence of variable thermal conductivity with chemical reaction effects. Jha and Aina (2018) studied role of suction/injection on steady fully developed mixed convection flow in a vertical parallel plate microchannel. Ajibade and Ojeagbase (2020) investigated steady natural convection heat and mass transfer flow through a vertical porous channel with viscosity and thermal conductivity. The variability in viscosity and thermal conductivity are considered linear function of temperature. The governing equations are transformed into a set of coupled nonlinear ordinary differential equations. Results obtained were compared with exact solution when some of the flow conditions were relaxed and results from differential transformation method show an excellent agreement with the exact solution which was obtained analytically. The effects of the thermophoresis, viscous dissipation and joule heating on steady MHD flow over an inclined radiative isothermal permeable surface with variable thermal conductivity was accomplished by Reddy (2013).

To the best of our knowledge the problem of Heat and Mass transfer flow in a channel filled with porous medium in the presence of variable thermal conductivity has not been studied. The aim of the present study is to investigate the effect of chemical reaction parameter as well as porosity parameter, Schmidt number, mass Grashof number, temperature buoyancy parameter, mass buoyancy parameter and magnetic field parameter on heat mass transfer flow with temperature dependent thermal conductivity.

MATERIALS AND METHODS

Formulation of the Problem

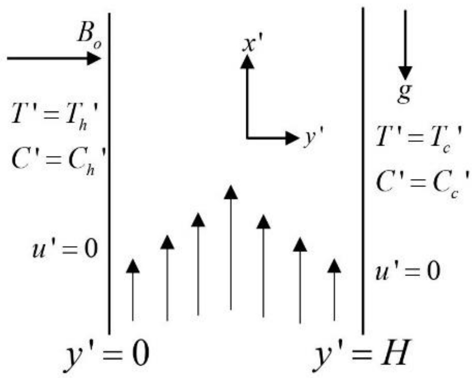


Figure 1: Geometry of the Problem

From figure 1; Consider steady, natural convections, heat and mass transfer flow of an electrically, conducting incompressible viscous fluid, having temperature dependent thermal conductivity between two vertical walls under the influence of a uniform transverse magnetic field of strength B_o.It is assumed that both the fluid and the walls are at rest and maintained at a constant temperature T_m' and the mass concentration C_m'. At time $t' > 0$, the wall is maintained at uniform temperature T_h' and uniform concentration C_h' which are higher than T_c' and C_c' respectively. We choose a Cartesian coordinate system with x' axis along the upward direction and the y' axis normal to it. Thermal conductivity (k_f) which obeys linear temperature law according to $k_f = k_m[1 + \delta(T' - T_m')]$, where k_m is the fluid free thermal conductivity and $\delta$is a constant dependent on the fluid ($\delta > 0$ for lubrication oils, hydromagnetic working fluids and $\delta > 0$ for air or water). Under these assumptions, along with Boussinesq's approximation, the governing equations for momentum, energy, and continuity in laminar incompressible boundary layer flow can be written as:

$$\frac{\partial U'}{\partial t'} = v\frac{\partial^2 U'}{\partial y'^2} + g\beta(T' - T'_m) - \frac{\sigma B_o^2 U'}{\rho} + g\beta^*(C' - C'_m) - \frac{1}{k}U' \quad (1)$$

$$\frac{\partial T'}{\partial t'} = \frac{1}{\rho c_p}\frac{\partial}{\partial y'}\left[k_f\frac{\partial T'}{\partial y'}\right] \quad (2)$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y'^2} - k^*(C' - C'_m) \quad (3)$$

The corresponding initial and boundary conditions are prescribed as follows:

$t' \le 0;\quad U' = 0, T' = T'_m, C' = C'_m, for 0 \le y' \le H$

$t' > 0;\quad U' = 0, T' = T'_h, C' = C'_h,\quad a\quad ty\quad ' = 0$

$U' = 0, T' = T'_c, C' = C'_c,\quad a\ \ ty\quad ' = H \quad (4)$

where $v, \sigma, \rho$are kinematic viscosity, conductivity of the fluid and density respectively, g, β, β^* are gravitational force, coefficient of the thermal expansion and concentration expansion coefficient respectively, $D, B_o, c_p$are chemical molecular diffusivity, electromagnetic induction and specific heat at constant pressure respectively, $t', T', C'$are time, fluid temperature and concentration respectively, $u' and v'$are velocity components in $x\ and\ y$directions respectively, $k^* and Da$are chemical reaction rate and porosity. $T_m', T_h', T'_c$are initial temperature of the fluid, temperature of the wall at $y' = 0$, temperature of the wall at $y' = H$respectively, $C_m', C_h', C'_c$are initial concentration of the fluid, concentration of the wall at $y' = 0$, concentration of the wall at $y' = H$respectively.

The non-dimensional quantities introduced in the above equations are as follows:

$$y = \frac{y'}{H}, t = \frac{t'v}{H^2}, U = \frac{U'v}{g\beta(T'_h - T'_m)H^2}, Sc = \frac{v}{D}, Pr = \frac{v\rho c_p}{k_m}, Da = \frac{Kv}{H^2}$$

$$M^2 = \frac{\sigma B_o^2 H^2}{v\rho}, Gc = \frac{g\beta^*(C' - C'_m)}{g\beta(T'_h - T'_m)}, \lambda = \delta(T'_h - T'_m), Kr = \frac{H^2 k^*}{v}, \frac{1}{Da} = \frac{H^2}{Kv} \quad (5)$$

$$\theta = \frac{T' - T'_m}{T'_h - T'_m},\ C = \frac{C' - C'_m}{C'_h - C'_m}, R = \frac{T'_c - T'_m}{T'_h - T'_m},\ Rc = \frac{C'_c - C'_m}{C'_h - C'_m}$$

Applying (5) to (1), (2), (3), (4), the following governing equations in non-dimensional form are obtained:

$$\frac{\partial U}{\partial t} = \frac{\partial^2 U}{\partial y^2} + \theta - M^2 U + GcC - \frac{1}{Da}U \quad (6)$$

$$Pr\frac{\partial \theta}{\partial t} = (1 + \lambda\theta)\frac{\partial^2 \theta}{\partial y^2} + \lambda\left(\frac{\partial \theta}{\partial y}\right)^2 \quad (7)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - KrC, \quad (8)$$

with the following initial and boundary conditions in dimensionless form:

$t \le 0;\quad U = 0, \theta = 0, C = 0, f\quad orally$

$t > 0;\quad U = 0, \theta = 1, C = 1, a\quad ty = 0$

$U = 0, \theta = R, C = Rc, a\ \ ty = 1 \quad (9)$

where Pr is the Prandtl number, Sc is the Schmidt number, Gc is the Solutal Grashof number, M is the Magnetic field parameter, λ is the variable thermal conductivity, Rc is the mass buoyancy parameter, R is the temperature buoyancy parameter, Kr is the chemical reaction parameter and Da is the porosity parameter.

Analytical Solutions

The analytical solutions have played significant role in validating and exploring computer routines of complicated problems. The governing equation (6), (7) and (8) will be reduce into a form that can be solve analytically using perturbation series methods. Therefore, by setting the partial derivatives: $\partial U/\partial t = 0, \partial\theta/\partial t = 0$and $\partial C/\partial t = 0$, into the equation (6), (7) and (8), the equations becomes:

$$\frac{d^2 U}{dy^2} + \theta - M^2 U + GcC - \frac{1}{Da}U = 0 \quad (10)$$

$$(1 + \lambda\theta)\frac{d^2\theta}{dy^2} + \lambda\left(\frac{d\theta}{dy}\right)^2 = 0 \quad (11)$$

$$\frac{1}{Sc}\frac{d^2 C}{dy^2} - KrC = 0 \quad (12)$$

The boundary conditions are:

$U = 0, \theta = 0, C = 0, f\quad or\ all\ y$

$U = 0, \theta = 1, C = 1,\quad at\ y\ 0$

$U = 0, \theta = R, C = Rc,\quad at\ \ y = 1 \quad (13)$

The steady state solutions of (10) to (12) subject to (13), we use perturbation method of the form:

$$U = U_0 + \lambda U_1$$
$$\theta = \theta_0 + \lambda\theta_1 \quad (14)$$
$$C = C_0 + \lambda C_1$$

Substituting (13) into (10) to (12), the solution of the governing equations is obtained as:

$$U = D_1 \cosh r\, y + D_2 \sinh r\, y + D_3 y + D_4 + D_5 \cosh\gamma\, y + D_6 \sinh\gamma\, y + \lambda E_1 \cosh r\, y$$
$$+\lambda E_2 \sinh r\, y + \lambda E_3 y^2 + \lambda E_4 y + \lambda E_5 + \lambda E_6 \cosh\gamma\, y + \lambda E_7 \sinh\gamma\, y \quad (15)$$

$$\theta = a_1 y + a_2 - \lambda \frac{{a_1}^2 y^2}{2} + \lambda b_1 y + \lambda b_2 \quad (16)$$

$$C = G_1 \cosh\gamma\, y + G_2 \sinh\gamma\, y + \lambda H_1 \cosh\gamma\, y + \lambda H_2 \sinh\gamma\, y \quad (17)$$

The Skin friction from the velocity is given by:

$$\left.\frac{dU}{dy}\right|_{y=0} = rD_2 + D_3 + \gamma D_6 + r\lambda E_2 + \lambda E_4 + \gamma\lambda E_7$$

$$\left.\frac{dU}{dy}\right|_{y=1} = rD_1 \sinh r + rD_2 \cosh r + D_3 + \gamma D_5 \sinh\gamma + \gamma D_6 \cosh r + r\lambda E_1 \sinh r$$
$$+ r\lambda E_2 \cosh r + 2\lambda E_3 + \lambda E_4 + \gamma\lambda E_6 \sinh\gamma + \gamma\lambda E_7 \cosh\gamma \quad (18)$$

Similarly, the Nusselt number become:

$$\left.\frac{d\theta}{dy}\right|_{y=0} = a_1 + \lambda b_1$$

$$\left.\frac{d\theta}{dy}\right|_{y=1} = -{a_1}^2\lambda + a_1 + \lambda b_1 \quad (19)$$

While, the Sherwood number is:

$$\left.\frac{dC}{dy}\right|_{y=0} = \gamma G_2 + \gamma\lambda H_2$$

$$\left.\frac{dC}{dy}\right|_{y=1} = \gamma G_1 \sinh\gamma + \gamma G_2 \cosh\gamma + \gamma\lambda H_1 \sinh\gamma + \gamma\lambda H_2 \cosh\gamma \quad (20)$$

RESULTS AND DISCUSSION

In this paper, the main objectives are to analyze the effect of various parameters on heat mass transfer flow in a channel filled with porous medium in the presence of variable thermal conductivity. The solutions are simulated for different values of magnetic field M, Schmidt number Sc, mass Grashof number Gc, buoyancy force distribution R, mass buoyancy Rc, chemical reaction Kr, porosity Da and thermal conductivity λ were obtained.

Figure 2 and 3 represents the concentration profiles for various values of chemical reaction and Schmidt number parameter. In Figure 2, it is observed that, the concentration decrease with increase in chemical reaction parameter Kr likewise for the Schmidt number parameter Sc in Figure 3.

The temperature profiles have been studied and illustrated in Figure 4 and Figure 5 for various values of thermal conductivity and buoyancy force distribution parameters shown in Figures 4 and 5 respectively.

Figure 4 and 5 shows that, the temperature increase with increase of thermal conductivity parameter λ and similarly for the buoyancy force distribution parameter R.

Figures 6 to 9 illustrates the velocity profiles for various values of porosity, mass Grashoff number, mass buoyancy ratio and magnetic field parameter.

Figure 6 shows that the velocity decreases with increasing porosity parameter Da. But, Figure 7 indicates that, the velocity increase whenever mass Grashoff number Gc increases. While from Figure 8, it found that, the velocity increase with increasing mass buoyancy parameter Rc. Further, Figure 9 displays that, the velocity increase when the magnetic field parameter M increased.

Figure 10 to 15 are for the Sherwood number, Nusselt number and skin friction for the analytical solution.

Figure 10 and 11 displays the effect of thermal conductivity λ and Schmidt number Sc on fluid Sherwood number for both y = 0 and y = 1 and it is clearly seen that the Sherwood number in Figure 10 and 11 (a) get reduced by increasing both thermal conductivity parameter λ and Schmidt number Sc. While in figure 10 and 11 (b), fluid Sherwood number gets intensified with increase in thermal conductivity parameter λ and Schmidt number Sc.

Figure 12 and 13 illustrates the effect of buoyancy force distribution R and thermal conductivity λ on fluid Nusselt number for both y = 0 and y = 1 respectively and it is clearly seen that the Nusselt number in Figure 12, gets reduced with increase of buoyancy force distribution parameter R. While in Figure 13, fluid Nusselt number gets reduced by increasing thermal conductivity parameter λ at y = 0 and gets enhanced by increasing thermal conductivity parameter λ at y = 1.

Figure 14 and 15 represents the effect of porosity parameter Da and chemical reaction parameter Kr on the fluid skin friction for both y = 0 and y = 1 respectively. It is clearly seen that the fluid skin fiction in Figure 14 (a) gets enhanced by increasing porosity parameter Da just like Figure 15 (b) which found, that the fluid skin friction gets intensified with increase in chemical reaction parameter Kr. While in Figure 14 (b) the fluid skin friction gets reduced by increasing porosity parameter Da. Also, the fluid skin friction in Figure 15 (a) gets reduced by increasing chemical reaction parameter Kr.

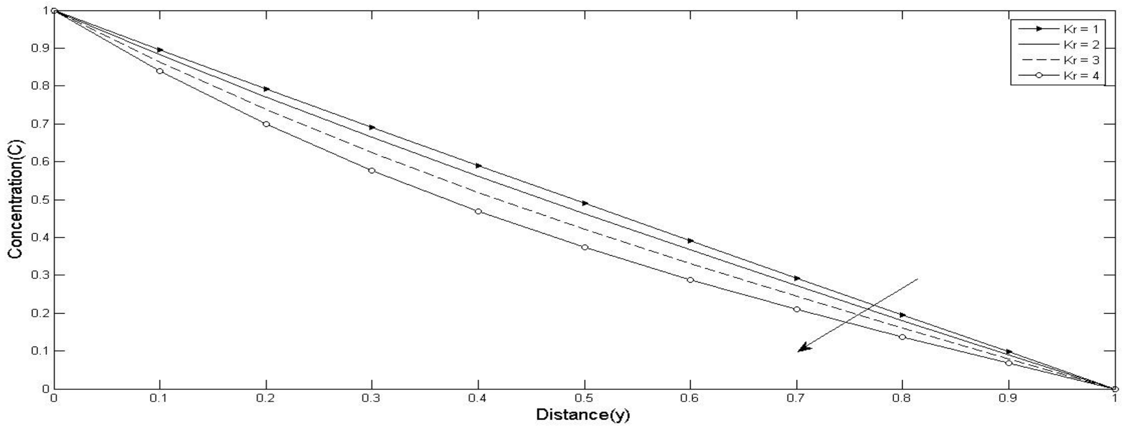


Figure 2: Effect of various value of Kr on concentration profile.

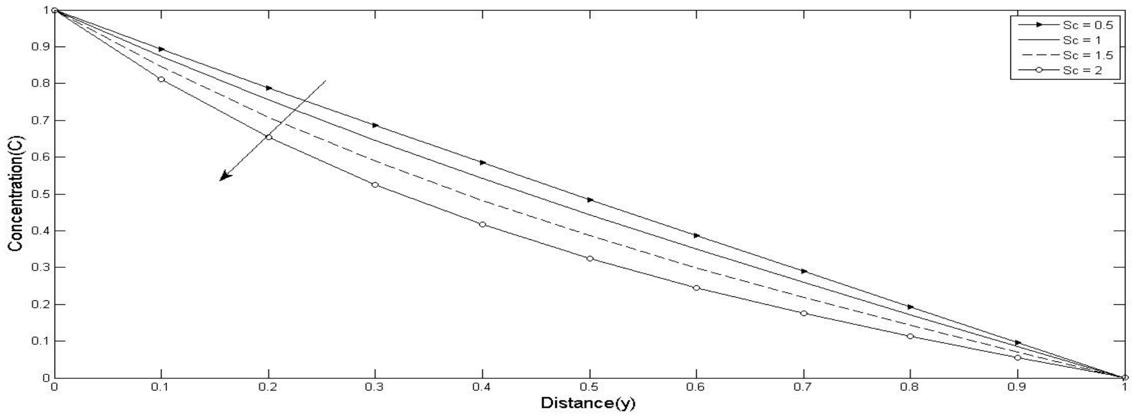


Figure 3: Effect of various value of Sc on concentration profile.

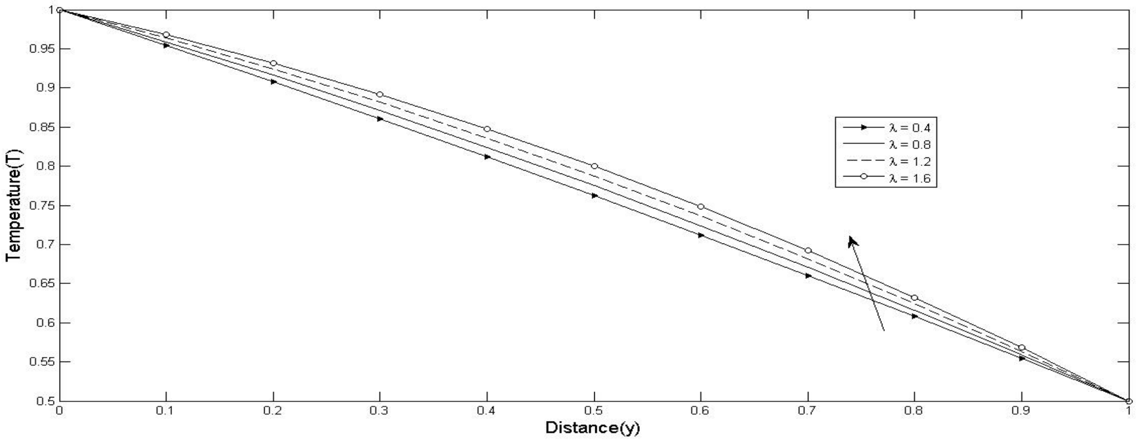


Figure 4: Effect of various value of λ on temperature profile.

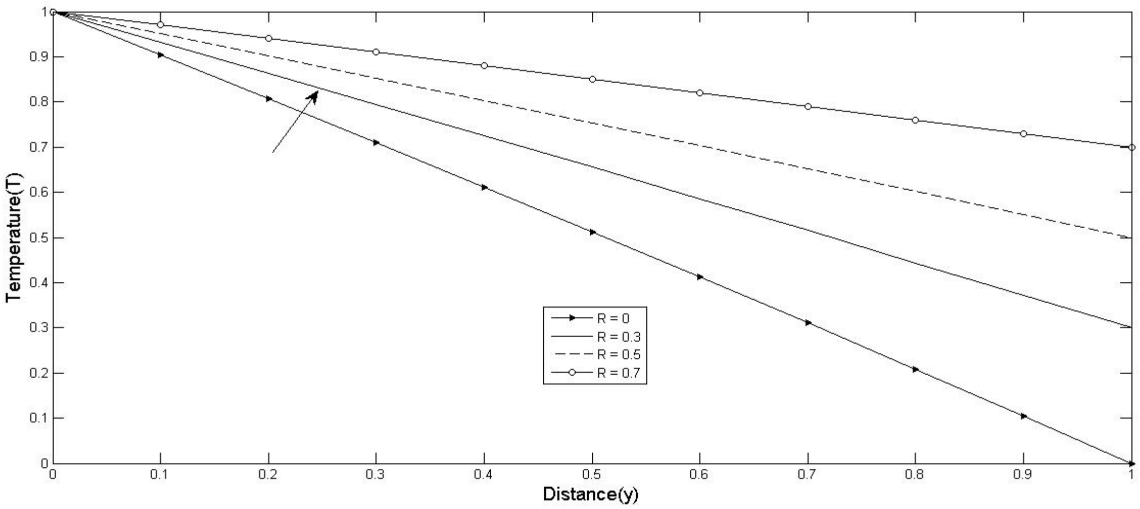


Figure 5: Effect of various value of R on temperature profile.

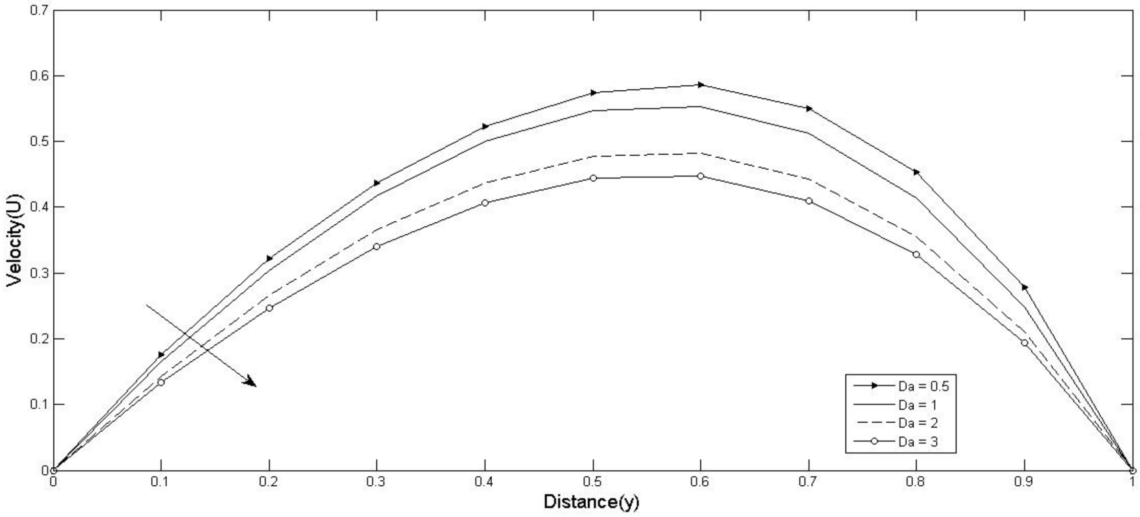


Figure 6: Effect of various value of Da on velocity profile.

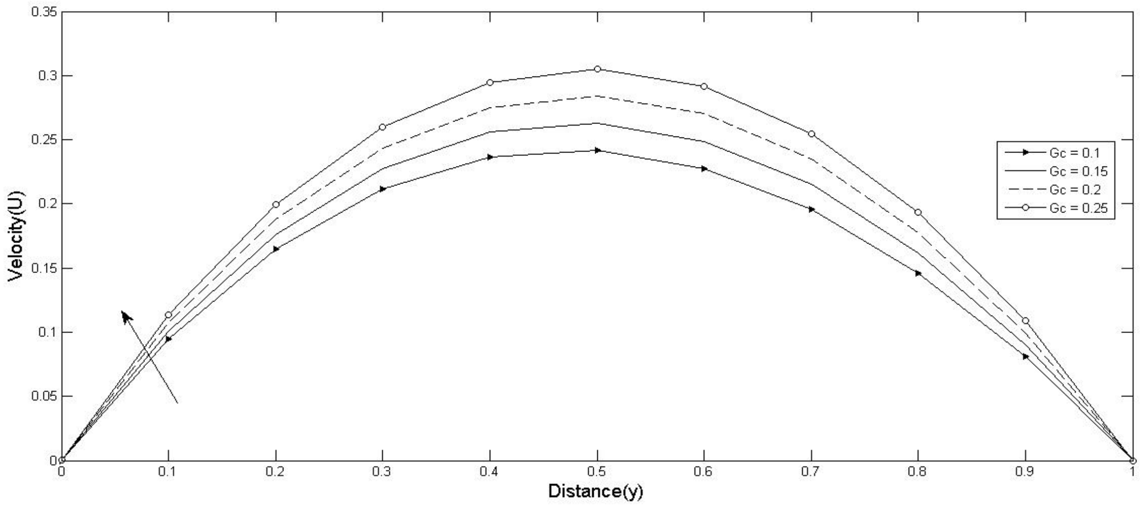


Figure 7: Effect of various value of Gc on velocity profile.

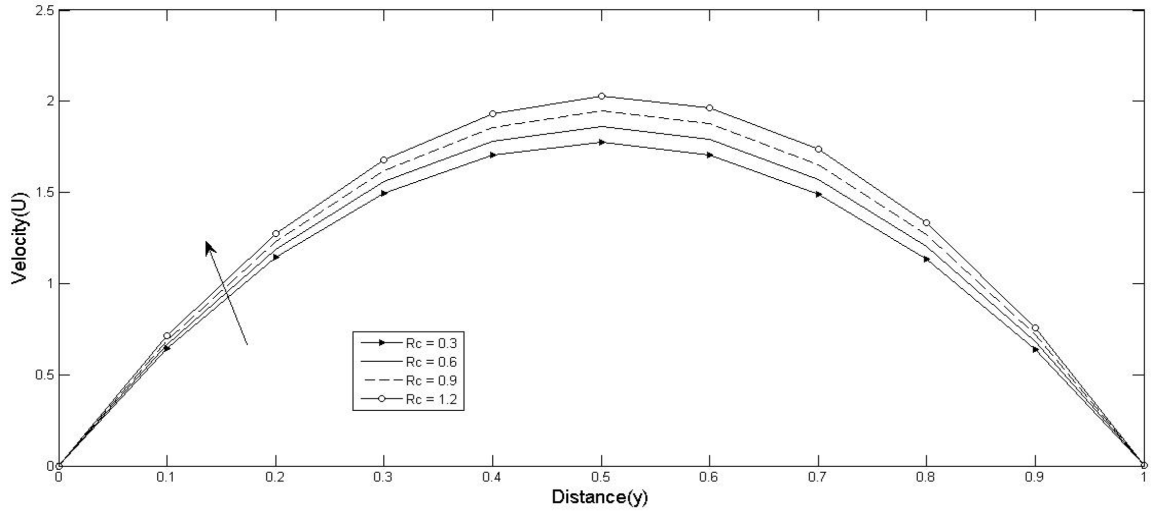


Figure 8: Effect of various value of Rc on velocity profile.

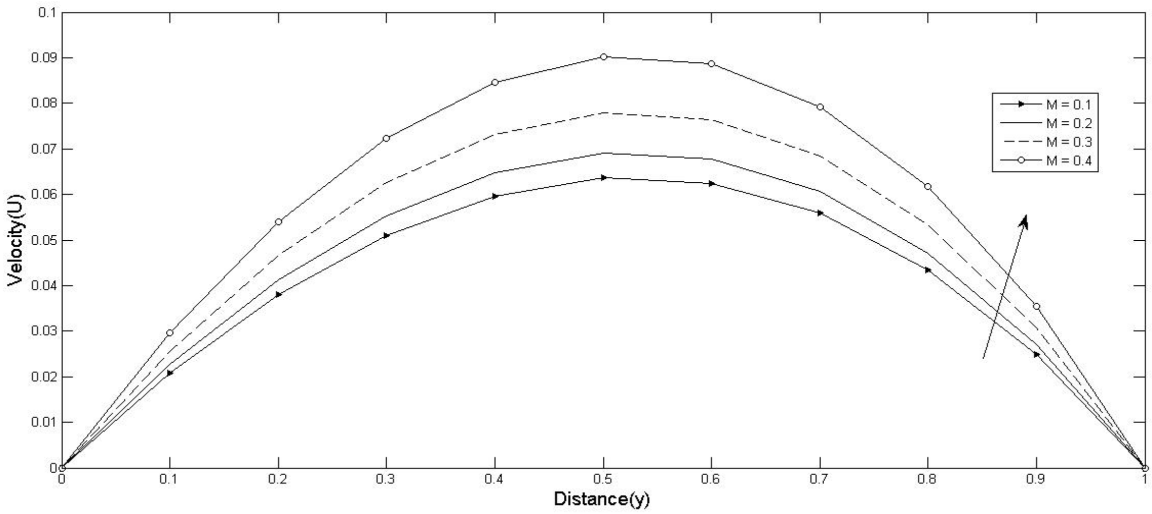
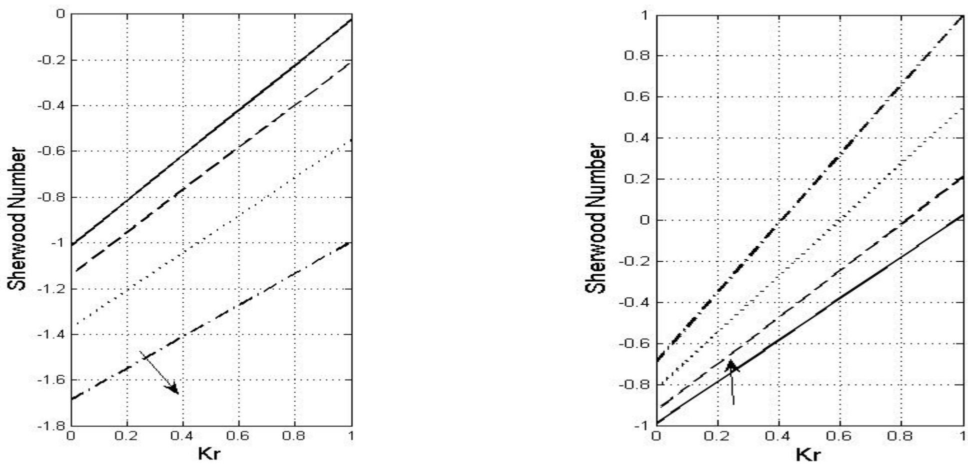
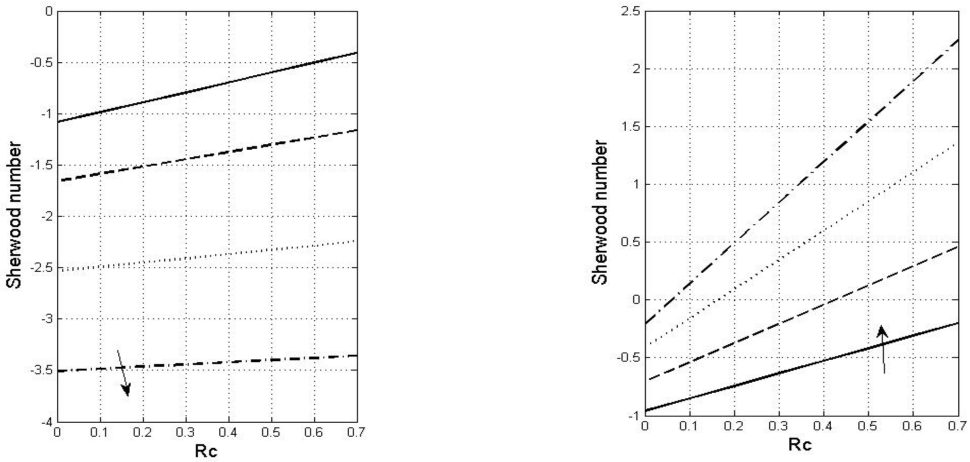


Figure 9: Effect of various value of M on velocity profile.



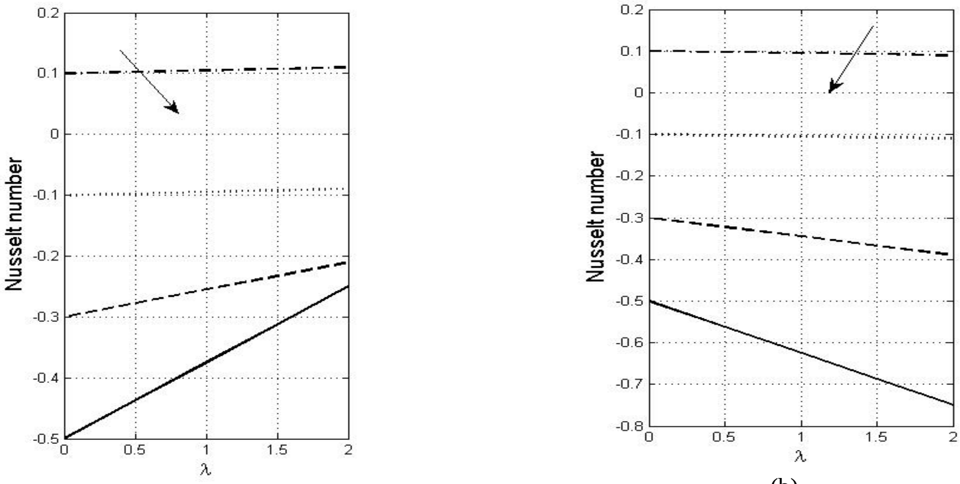
(a) (b)

Figure 10: Effect of Sherwood number with Kr and λ at y = 0 and y = 1



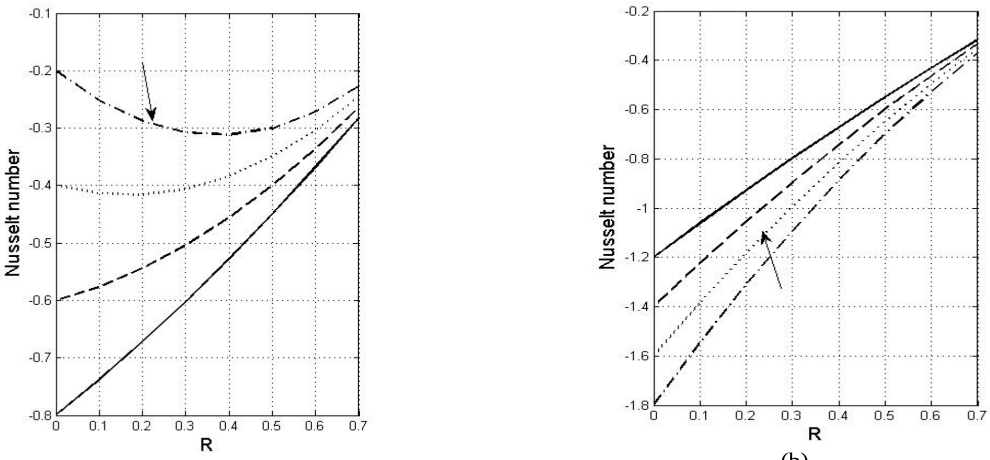
(a) (b)

Figure 11: Effect of Sherwood number with Rc and Sc at y = 0 and y =1



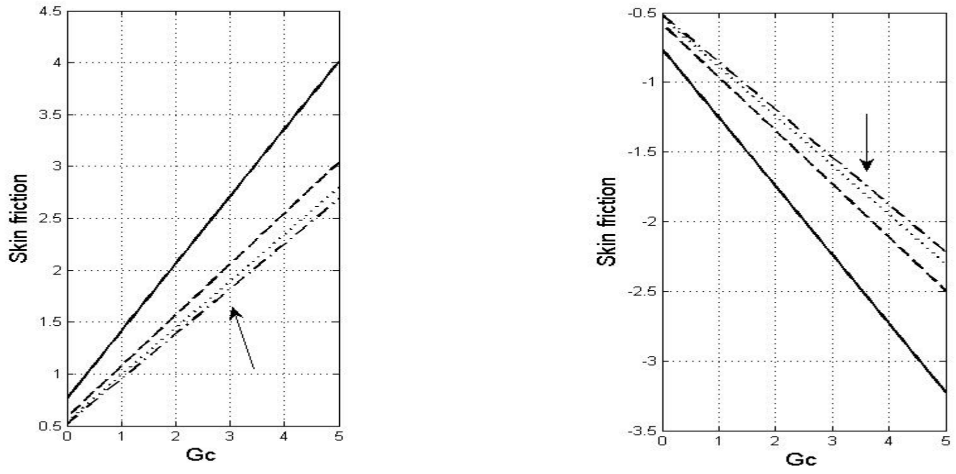
(a) (b)

Figure 12: Effect of Nusselt number with λ and R at y = 0 and y = 1



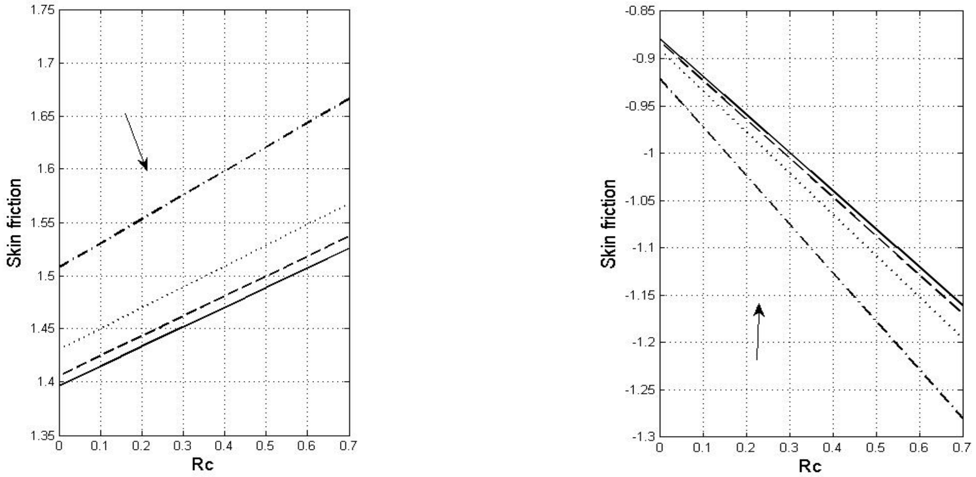
(a) (b)

Figure 13: Effect of Nusselt number with R and λ at y = 0 and y = 1



(a) (b)

Figure 14: Effect of skin friction with Gc and Da at y = 0 and y = 1



(a) (b)

Figure 15: Effect of skin friction with Rc and Kr at y = 0 and y = 1.

CONCLUSION

The present work analyzes the steady state free convection with heat and mass transfer in the presence of variable thermal conductivity. Dimensionless governing equations were solved analytically using the perturbation technique. Analytical solutions obtained are presented in graphs for the fluid flow and heat mass transfer characteristics for different values of parameters involved in the problem. From the study, the following conclusions were drawn; Increase of, mass Grashof number Gc, mass buoyancy parameter Rc and magnetic field parameter λ enhances the velocity while reverse is the case with increase of porosity parameter Da. An increase in temperature is a function of an increase in buoyancy force parameter R, and thermal conductivity parameter λ, and the concentration decreased due to increases in mass buoyancy parameter Rc and Schmidt number parameter Sc. At y = 0, the skin friction increases with increase of porosity parameter Da and slightly decreases with of chemical reaction parameter Kr. Similarly, at y = 1, skin friction gets reduced with increase of porosity parameter Da and it also enhances the skin friction with increase of chemical reaction parameter Kr. Increase in buoyancy force distribution R and thermal conductivity parameter λ diminishes Nusselt number at y = 0. Increase in thermal conductivity parameter λ also it enhances the fluid Nusselt number at y = 1, increase in buoyancy force distribution parameter R diminishes the Nusselt number at y = 1. Increase in thermal conductivity parameter λ, and mass buoyancy parameter Rc diminishes the fluid Sherwood number at y = 0, but increases at y = 1.

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