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RADIATION AND MASS TRASFNER EFFECTS ON UNSTEADY HYDROMAGNETIC FREE CONVECTION FLOW THROUGH POROUS MEDIUM PAST A VERTICAL PLATE WITH HEAT FLUX

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Abstract: An analytical solution for simultaneous effects of thermal and concentration diffusions in unsteady magnetohydrodynamic free convection flow past a moving plate maintained at constant heat flux and embedded in a viscous fluid saturated porous medium is presented. The transported model employed includes the effects of thermal radiation and chemical reaction. Te fluid is considered as a gray absorbing – emitting but non-scattering medium and the Rosseland approximation in the energy equation is used to describe the radiative heat flux for optically thick fluid. The dimensionless coupled linear partial differential equations are solved by suing perturbation technique. The solution for the velocity, temperature and concentration as well as the skin friction coefficient and the rates of heat and mass transfer are shown graphically for different values of physical parameters involved.

Keywords: Magnetic field, Free convection, Porous medium, Heat flux, Chemical reaction

1. Introduction

Free convection and mass transfer flow in porous medium has received considerable attention due to its numerous applications in geophysics and energy related problems such types of applications includes natural circulation in isothermal reservoirs, aquifers, porous insulation in heat storage bed, grain storage, extraction of thermal energy and thermal insulation design. Muthucumaraswamy et.al [1] investigated the flow past an impulsively started infinite vertical plate in the presence of uniform heat and mass flux at the plate and presented an exact solution using Laplace transforms technique. Chaudhary and Jain [2] have also studied combined heat and mass transfer effects on MHD free convection flow past an oscillating plate, whereas Sivaiah et.al [3] and Das and Jana [4] have studied hat and mass transfer effects on MHD free convection flow past a vertical plate with different boundary conditions.

Studies associated with flows through porous medium in rotating environment have some relevance in geophysical and geothermal applications. Many studies, with applications, are gathered in a comprehensive review of convective heat transfer mechanisms through porous media in the book by Nield and Bejan [5]. Also, several researchers considered hydromagnetic natural convection flow past a porous plate considering different aspects of the problem. Mention may be made of the research studies of Chamkha [6, 7], Kim [8], Rajesh and Varma [9]. In view of such applications, Sattar [10] has discussed the free convection and mass transfer flow through a porous medium past an infinite vertical porous plate with time-dependent temperature and concentration.

The study of convective flow with heat and mass transfer under the influence of chemical reaction has practical applications in many areas of science and engineering. This phenomenon plays an important role in the chemical industry, petroleum industry, cooling of nuclear reactors, and packed – bed catalytic reactors so that it has received a considerable amount of attention in recent years. Also, the study of chemical reaction with heat transfer in a porous medium has important engineering applications such as tubular reactors, oxidation of solid materials and synthesis of ceramic materials. Intensive studies have been carried out to investigate effects of chemical reaction on different flow and fluid types. The effects of chemical reaction and variable viscosity on hydromagnetic mixed convection heat and mass transfer of Hiemenz flow through porous media with radiation were studied by Seddeek et.al [11]. Mahdy [12] investigated the effect of chemical reaction and heat generation or absorption on double diffusive convection from a vertical truncated cone in a porous media with variable viscosity, whereas Alharbi et.al [13] presented the convective heat and mass transfer of an incompressible MHD Visco-elastic fluid flow immersed in a porous medium over a stretching sheet with chemical reaction and thermal stratification effects. Shateyi and Motsa [14] studied the problem of unsteady MHD convective heat and mass transfer past an infinite vertical plate in porous medium with thermal radiation in the presence of heat generation/absorption and chemical reaction. Mohamed Abd El-Aziz et.al [15] investigated heat and mass transfer of unsteady hydromagnetic free convection flow through porous medium past a vertical plate with uniform surface heat flux. Ch Kesavaiah et.al [16] analyzed effects of the chemical reaction and radiation absorption on an unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate embedded in a porous medium with heat source and suction. Karunakar Reddy et.al. [17] considered MHD heat and mass transfer flow of a viscoelastic fluid past an impulsively started infinite vertical plate with chemical reaction. Omeshwar Reddy. V, Neelima. A et. al.(18) discussed the Finite difference solutions of MHD natural convective visco elastic fluid flow past a vertically inclined porous plate in presence of thermal diffusion, diffusion thermo, heat and mass transfer effects. Srinathuni Lavanya and Chenna Kesavaiah [19] studied heat transfer to MHD free convection flow of a viscoelastic dusty gas through a porous medium with chemical reaction. Mallikarjuna Reddy et.al. [20] investigated effects of radiation and thermal diffusion on MHD heat transfer flow of a dusty viscoelastic fluid between two moving parallel plates. Bhavana and Chenna Kesavaiah [21] worked out perturbation solution for thermal diffusion and chemical reaction effects on MHD flow in vertical surface with heat generation. Mallikarjuna Reddy et. al. [22] analyzed radiation and diffusion thermo effects of viscoelastic fluid past a porous surface in the presence of magnetic field and chemical reaction with heat source. Omeshwar Reddy. V, Thiagarajan. S (23) analyzed the visco elastic fluid effect on mixed convective fluid flow past a wavy inclined porous plate in presence of soret, dufour, heat source and thermal radiation. Chenna Kesavaiah and Venkateswarlu [24] has been considered chemical reaction and radiation absorption effects on convective flows past a porous vertical wavy channel with travelling thermal waves. Srinathuni Lavanya et. al. [25] motivated radiation effect on unsteady free convective MHD flow of a viscoelastic fluid past a tilted porous plate with heat source. Chenna Kesavaiah et. al. [26] motivated study on radiative MHD Walter's Liquid-B flow past a semi-infinite vertical plate in the presence of viscous dissipation with a heat source. Rami Reddy et. al. [27] explained hall effect on MHD flow of a visco-elastic fluid through porous medium over an infinite vertical porous plate with heat source. Chenna Kesavaiah and Venkateswarlu [28] discussed chemical reaction and radiation absorption effects on convective flows past a porous vertical wavy channel with travelling thermal waves. Nagaraju et. al. [29] studied Radiation and chemical reaction effects on MHD casson fluid flow of a porous medium with suction/injection.

The present paper consist of an analytical solution for simultaneous effects of thermal and concentration diffusions in unsteady magnetohydrodynamic free convection flow past a moving plate maintained at constant heat flux and embedded in a viscous fluid saturated porous medium is presented. The transported model employed includes the effects of thermal radiation and chemical reaction.

2. Formulation of the problem

Consider an unsteady one-dimensional flow of an incompressible, electrically conducting and viscous fluid past an infinite vertical plate embedded in a porous medium with constant heat flux at $y^* = 0$. The $x^* -$axis is measured along the plate in the upward direction and $y^* -$ axis is measured normal to the plate in the outward direction. A uniform magnetic field B_0 is acting in the transverse direction to the flow.

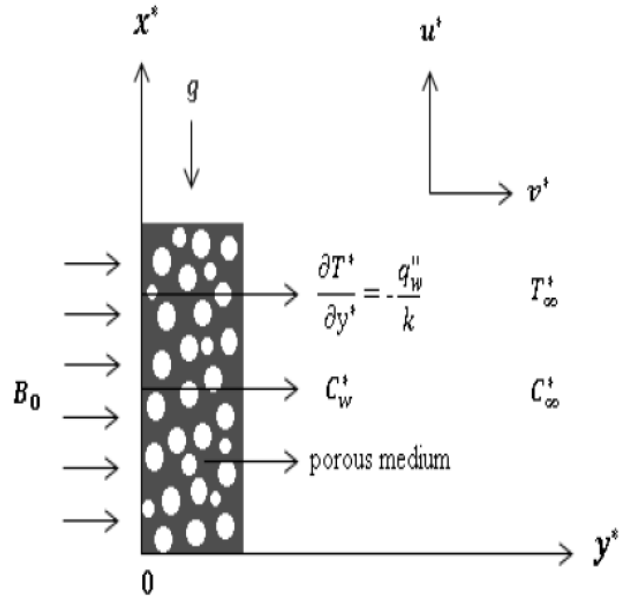

Figure (1): Flow geometry and physical coordinate system

The transversely applied magnetic field and magnetic Reynolds number are assumed to be very small so that the induced magnetic field and the Hall Effect are negligible. The Soret and thermal buoyancy effects are also considered. The plate is infinite in length, so all the field quantities become functions of space coordinate y^* and time t^*. Initially, the plate and the fluid are at same temperature T_∞^* and concentration C_∞^*. Subsequently, at time $t^* > 0$, the plate begins to move in its own plane and accelerates against the gravitational field with uniform acceleration $f\left(t^*\right)$ in x^*-direction. Simultaneously, heat is supplied form the surface of the plate to the fluid, which is maintained throughout the fluid flow at the uniform rate $\frac{q_w''}{k}$ and concentration level is raised to C_w'' as shown in figure (1). Under the above assumptions and invoking the Boussinesq approximation, the governing equations of momentum, energy and concentration are derived as follows:

$$\frac{\partial u^*}{\partial t^*} = \nu \frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\sigma B_0^2}{\rho} u^* - \frac{\nu}{K^*} u^* + g\,\beta\left(T^* - T_\infty^*\right) + g\,\beta^*\left(C^* - C_\infty^*\right) \tag{2.1}$$

$$\rho c_p \frac{\partial T^*}{\partial t^*} = \kappa \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{\partial q_r^*}{\partial y^*} \tag{2.2}$$

$$\frac{\partial C^*}{\partial t^*} = \kappa \frac{\partial^2 C^*}{\partial y^{*2}} - Kr^*\left(C^* - C_\infty^*\right) \tag{2.3}$$

The initial and boundary conditions are:

$$\begin{aligned} &u^* = 0, T^* = T_\infty^*, C^* = C_\infty^* && \textit{for all} \quad y^* \geq 0,\ t^* \leq 0 \\ &u^* = f\left(t^*\right), \frac{\partial T^*}{\partial y^*} = -\frac{q_w''}{k}, C^* = C_\infty^* && \textit{at} \quad y^* = 0,\ t^* > 0 \\ &u^* \to 0, T^* \to T_\infty^*, C^* \to C_\infty^* && \textit{as} \quad y^* \to \infty \end{aligned} \tag{2.4}$$

in which $f\left(t^*\right)$ is the uniform acceleration of the plate, x^* and y^* are the distances along and perpendicular to the plate, t^* is the dimensional time, u^* is the fluid velocity in the $x^* -$direction, T^* is the temperature of the fluid, T_∞^* is the free stream temperature, C^* is the concentration, C_w^* is the surface concentration, C_∞^* is the free stream concentration, Q_0 is the dimensional heat absorption coefficient, κ is the thermal conductivity, q_r^* is the radiative heat flux in $x^* -$direction, q_w'' is the constant heat flux per unit area at the plate, β is the volumetric coefficient of thermal expansion, β^* is the volumetric coefficient of expansion for concentration, ν is the kinematic viscosity, μ is the fluid viscosity, ρ is the fluid density, c_p is the specific heat capacity, σ is the electrical conductivity of the fluid, K^* is the permeability of the porous medium, T_m is the mean fluid temperature, K_T is the thermal-diffusion ratio, Kr^* is the chemical reaction constant and D is the mass diffusivity.

The radiative heat flux q_r^* under Rosseland approximation has the form

$$q_r^* = -\frac{4\sigma^*}{3k^*}\frac{\partial T^{*4}}{\partial y^*} \tag{2.5}$$

where σ^* is the Stefan – Boltzmann constant and k^* is the mean absorption coefficient. It is assumed that the temperature differences within the flow are sufficiently small such that T^{*4} may be expressed as a linear function of the temperature. This is accomplished by expanding T^{*4} in a Taylor series about T_∞^* using Taylor series expansion and neglecting the higher order terms, we get

$T^{*4} \cong 4T^{*3}_\infty T' - 3T^{*4}_\infty$ gives

$$q_r^* = -\frac{16a^*\sigma T^{*3}_\infty}{3k^*}\frac{\partial T^*}{\partial y^*} \tag{2.6}$$

From (6), (2) reduces to the following form:

$$\rho c_p \frac{\partial T^*}{\partial t^*} = \kappa \frac{\partial^2 T^*}{\partial y^{*2}} + \frac{16a^*\sigma T^{*3}_\infty}{3k^*}\frac{\partial^2 T^*}{\partial y^{*2}} \tag{2.7}$$

Now, we take $f\left(t^*\right) = At^*$ and define the following non-dimensional variables

$$y = y^* 3\sqrt{\frac{A}{\nu^2}},\ u = \frac{u^*}{3\sqrt{\nu A}},\ t = t^* 3\sqrt{\frac{A^2}{\nu}},\ \theta = \frac{T^* - T_\infty{}^*}{\frac{q_w''}{k}3\sqrt{\frac{\nu^2}{A}}},\quad C^* = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*} \tag{2.8}$$

where A denotes the uniform acceleration of the plate in $x-$direction, u is the dimensionless velocity, y is dimensionless coordinate perpendicular to the plate, t is the dimensionless time, θ is the dimensionless temperature and ϕ is the dimensionless concentration.

Substituting equations (2.8) into equation (2.1), (2.3) and (2.7) gives the governing equations in dimensionless form

$$\frac{\partial u}{\partial t}=\frac{\partial^2 u}{\partial y^2}-H\ Gr\,\theta+Gm\phi \tag{2.9}$$

$$F^*\frac{\partial \theta}{\partial t}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2}-L\theta \tag{2.10}$$

$$\frac{\partial \phi}{\partial t}=\frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2}-Kr\phi \tag{2.11}$$

with dimensionless initial and boundary conditions

$$\begin{aligned} &u=0,\theta=0,\phi=0 \quad \textit{for all} \quad y\ge 0,\ t\le 0\\ &u=t,\frac{\partial \theta}{\partial y}=-1,\ \ \phi=1 \quad at \quad y=0,\ t>0\\ &u\to 0,\theta\to 0,\phi\to 0 \quad as \ \ y\to\infty \end{aligned} \tag{2.12}$$

where

$$\begin{aligned} &M=\frac{\sigma B_0{}^2\,3\sqrt{\nu A}}{\rho A},Gr=\frac{\beta g q_w''\sqrt{\nu A}}{\rho A},Gm=\frac{\beta^* g\left(C_w^*-C_\infty^*\right)}{A}\\ &\frac{1}{K}=\frac{\nu\sqrt{\nu A}}{AK^*},\quad H=M+\frac{1}{K},\quad \Pr=\frac{\nu\rho c_p}{k},\quad R=\frac{16a^*T^{*3}_\infty}{3kk^*}\\ &F^*=\frac{\Pr}{1+R},\quad Sc=\frac{\nu}{D},\quad Kr=Kr^*\sqrt{\frac{\nu}{A^2}},\quad L=F^* \end{aligned} \tag{2.13}$$

where Gr is the thermal Grashof number, Gc is modified Grashof number, $\Pr$ is Prandtl number, M is the magnetic field, Sc is Schmidt number, Kr is Chemical reaction, K is Porous permeability respectively.

3. Solution of the problem

The well-posed problems defined by (2.9) – (2.11) will be solved by suing the perturbation technique. Exact analytical expression for dimensionless velocity, temperature and concentration fields will be separately obtained for $Sc\neq 1,\ Sc=1$. Therefore the fluid in the neighbourhood of the fluid in the neighbourhood of the plate as

$$\begin{aligned} u&=u_0(y)+\varepsilon e^{at}u_1(y)\\ \theta&=\theta_0(y)+\varepsilon e^{at}\theta_1(y)\\ \phi&=\phi_0(y)+\varepsilon e^{at}\phi_1(y) \end{aligned} \tag{3.1}$$

Substituting (3.1) in Equation (2.9) – (2.11) and equating the harmonic and non – harmonic terms, we obtain

$$u_0''-Hu_0=-Gr\,\theta_0-Gm\,\phi_0 \tag{3.2}$$

$$u_1''-\beta_3 u_1=-Gr\,\theta_1-Gm\phi_1 \tag{3.3}$$

$$\theta_0'' - L\theta_0 = 0 \tag{3.4}$$

$$\theta_1'' - \beta_1\theta_1 = 0 \tag{3.5}$$

$$\phi_0'' - KrSc\ \phi_0 = 0 \tag{3.6}$$

$$\phi_1'' - \beta_2\,\phi_1 = 0 \tag{3.7}$$

The corresponding boundary conditions can be written as

$$u = 0, \theta = 0, \phi = 0 \qquad for\ all \quad y \ge 0,\ t \le 0$$

$$u_0 = t, u\ \ = 0, \frac{\partial\theta_0}{\partial y} = -1, \frac{\partial\theta_1}{\partial y} = 0\ \ \phi_0 = 1,\ \phi_0 = 0 \quad at \quad y = 0,\ t > 0 \quad (3.8$$

$$u_0 \to 0, \theta_0 \to 0, \phi_0 \to 0, u_1 \to 0, \theta_1 \to 0, \phi_1 \to 0 \qquad as\ \ y \to \infty$$

Case (i): **For** $Sc \neq 1$

Solving Equations (3.2) - (3.7) under the boundary conditions (3.8) and we obtain the velocity, temperature and concentration distributions in the boundary layer as

$$u_0 = L_1 e^{-\sqrt{L}y} + L_2 e^{-\sqrt{KrSc}\ y} + L_3 e^{-\sqrt{H}y}; u_1 = 0$$

$$\theta_0 = \frac{1}{\sqrt{L}} e^{-\sqrt{L}\,y}; \theta_1 = 0$$

$$\phi_0 = e^{-\sqrt{KrSc}\ y}; \phi_1 = 0$$

In view of the equation (3.1) becomes

$$u = L_1 e^{-\sqrt{L}y} + L_2 e^{-\sqrt{KrSc}\ y} + L_3 e^{-\sqrt{H}y}$$

$$\theta = \frac{1}{\sqrt{L}} e^{-\sqrt{L}\,y}$$

$$\phi = e^{-\sqrt{KrSc}\ y}$$

Coefficient of Skin-Friction

The coefficient of skin-friction at the vertical porous surface is given by

$$C_f = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -\sqrt{L}\,L_1 - \sqrt{KrSc}\ L_2 - \sqrt{H}\,L_3$$

Coefficient of Heat Transfer

The rate of heat transfer in terms of Nusselt number at the vertical porous surface is given by

$$N_u = \left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -1$$

Sherwood number

$$Sh = \left(\frac{\partial \phi}{\partial y}\right)_{y=0} = -\sqrt{KrSc}$$

Case (ii): **For** $Sc = 1$

Solving Equations (3.2) - (3.7) under the boundary conditions (3.8) and we obtain the velocity, temperature and concentration distributions in the boundary layer as

$$u_0 = L_1 e^{-\sqrt{L}y} + L_2 e^{-\sqrt{\gamma}\, y} + L_3 e^{-\sqrt{H}y}; u_1 = 0$$

$$\theta_0 = \frac{1}{\sqrt{L}} e^{-\sqrt{L}\, y}; \theta_1 = 0$$

$$\phi_0 = e^{-\sqrt{\gamma}\, y}; \phi_1 = 0$$

In view of the equation (3.1) becomes

$$u = L_1 e^{-\sqrt{L}y} + L_2 e^{-\sqrt{Kr}\, y} + L_3 e^{-\sqrt{H}y}$$

$$\theta = \frac{1}{\sqrt{L}} e^{-\sqrt{L}\, y}$$

$$\phi = e^{-\sqrt{Kr}\, y}$$

Coefficient of Skin-Friction

The coefficient of skin-friction at the vertical porous surface is given by

$$C_f = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -\sqrt{L}\, L_1 - \sqrt{Kr}\; L_2 - \sqrt{H}\, L_3$$

Coefficient of Heat Transfer

The rate of heat transfer in terms of Nusselt number at the vertical porous surface is given by

$$N_u = \left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -1$$

Sherwood number

$$Sh = \left(\frac{\partial \phi}{\partial y}\right)_{y=0} = -\sqrt{Kr}$$

4. Results and discussions

We have formulated and solve the problem of the combined effects of heat and mass transfer with free convective MHD flow of an incompressible viscous fluid through a porous medium with constant heat flux at the plate. Final results are computed for a variety of physical parameters, which are presented by means of graphs. The results are obtained to illustrate the effects of magnetic field parameter, dimensionless permeability parameter, Grashof numbers for heat and mass transfer, chemical reaction parameter, Prandtl number, heat source parameter, radiation parameter, Schmidt number and dimension less time on the velocity, temperature and concentration profiles, as well as the skin friction coefficient, Sherwood number.

Control of boundary layer flow is of practical significance. Several methods have been developed for the purpose of artificially controlling the behaviour of the boundary layer. The application of magnetohydrodynamic (MHD) principle is another method for affecting flow field in the desired direction by altering the structure of the boundary layer. Figure (2) shows the velocity profiles for various values of magnetic parameter (M). The velocity curves show that the rate of transport is remarkably reduced with increase of magnetic parameter. This result agrees qualitatively with the expectations, since the magnetic field exerts a retarding effect on the free convective flow. The variation of velocity profiles with dimensionless permeability parameter is presented in figure (3). This figure clearly indicates that the value of velocity profiles increases with increasing the dimensionless permeability parameter. Physically, this result can be achieved when the holes of the porous medium are very large so that the resistance of the medium maybe neglected. Figure (4) is plotted to show the effect of Grashof number (Gr) for heat transfer on the velocity profiles. It is observed that an increase in Grashof number lead to increase in the velocity. This is due to fact that buoyancy force enhances fluid velocity and increases the boundary layer thickness with increase in the values of Grashof number. It is also observed that distinctive peaks in the velocity profiles occur in the fluid adjacent to the wall for higher values of Grashof number. The presence of the peaks indicates that the maximum value of fluid velocity occurs in the body of the fluid close to the plate and not at the plate. Figure (5) illustrates the effect of Grashof number (Gc) for mass transfer on the velocity profiles. As seen from this figure that, the effect of Grashof number on the fluid velocity is the same as that Grashof number (Gr). This is the fact is achieved by comparing figure (4) and (5). Figure (6) represents the dimensionless velocity profiles for increasing values of chemical reaction parameter (Kr). It is seem this figure that augmenting values of chemical reaction parameter lead to fall in the velocity of the fluid. Figure (7) is sketched to show the effects of Prandtl number on velocity profiles. Four different realistic values of Prandtl number $(\Pr = 0.7, 1, 7, 100)$ that are physically correspond to air, electrolytic solution, water and engine oil respectively are chosen. It is observed that the velocity decreases with increasing values of Prandtl number. This is due to the fact that fluid with large Prandtl number has high viscosity and small thermal conductivity, which make the fluid thick and causes a decrease in fluid velocity. Figure (8) presents the effects of radiation parameter (R) on the velocity profiles. It is found that the velocity increases with increasing radiation parameter. This result happens due to the fact that the large radiation parameter values correspond to an increased dominance of conduction over radiation thereby increasing buoyancy force (thus, vertical velocity) and thickness of momentum boundary layer. Figure (9) shows the effect of Schmidt number on the velocity profiles for $Sc = 0.16$ (hydrogen), $Sc = 0.3$ (helium), $Sc = 0.6$ (water vapour), $Sc = 2.01$ (ethyl Benzene). It is observed that the velocity decreases with increasing Schmidt number values due to the decrease in the molecular diffusivity, which results in a decrease in the concentration and velocity boundary layer thickness. Variation of velocity profiles for different values of dimensionless time (t) is shown in figure (10). It is noticed that the velocity increases with the progression of time. Moreover, the velocity in this figure takes the values of time at the plate $(y = 0)$ and tends to zero for large values of y, which is a clear verification of the boundary conditions on the velocity given in equation (12). It is observed in figure (11) that the temperature (θ) increases as the radiation parameter (R) increases. This is because the large radiation parameter values correspond to an increased dominance of conduction over radiation thereby increasing the thickness of the thermal boundary layer. It is evident form figure (12), that as the values of Prandtl number $(\Pr)$ increase we can find a decrease in the temperature profiles and hence there is a decrease in thermal boundary layer thickness and more uniform temperature distribution across the boundary layer. Physically, this behaviour is due to the fact that with increasing Prandtl number, the thermal conductivity of the fluid decreases and the fluid viscosity increases which in turn results in a decrease in the thermal boundary layer thickness. Figure (13) observes the influence of Schmidt number (Sc) on the concentration (ϕ). It is evident from this figure that the increasing values of Schmidt number lead to fall in the concentration profiles. Physically, the increase of Schmidt number means a decrease of molecular diffusion D. Hence, the concentration of the species is higher for small values of Schmidt number and lower for large values of Schmidt number. The effect of chemical reaction parameter (Kr) on the concentration(ϕ) is shown in figure (14). It is noticed from this figure that there is a marked effect of increasing values of on concentration distribution in the boundary layer. It is clearly observed from this figure that increasing values of decrease the concentration of species in the boundary layer. This happens because large values of chemical reaction parameter reduce the solutal boundary layer thickness and increase the mass transfer. Variation of skin friction coefficient (τ) versus the dimensionless time (t) are plotted in figure (15) for various values of Prandtl number and Grashof number of heat transfer Gr. It is revealed form this figure that τ greatly increases as t increase for all values of $\Pr$ and Gr. It can be seen from figure (16) that the Sherwood number (Sh) is reduced with an increase of for all values of Schmidt number(Sc). Also, this figure illustrates that with increasing values of i Sc, Sh s increasing when $Kr \le K_0 \approx 0.1$ and it is decreasing when $Kr > K_0$.

Appendix

$$\beta_1 = \left(1 + F^* at\right), \beta_2 = \left(Kr + at\right)Sc, \beta_3 = \left(H + at\right)$$

$$L_1 = -\frac{Gr}{\sqrt{L}\left(L - H\right)}, L_2 = -\frac{Gc}{KrSc - H}, L_3 = \left(t - L_1 - L_2\right)$$

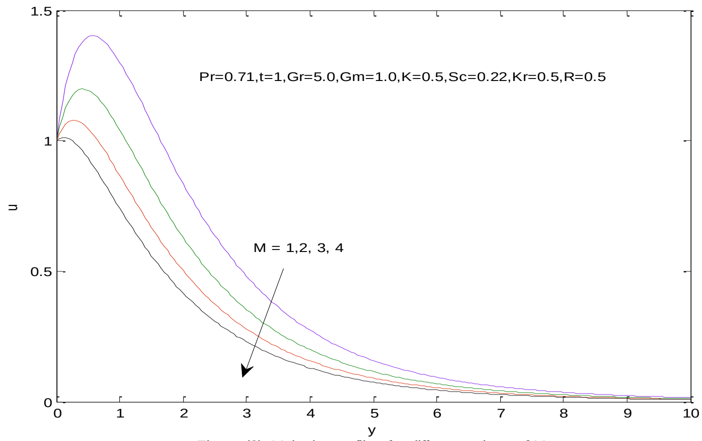

Figure (2): Velocity profiles for different values of M

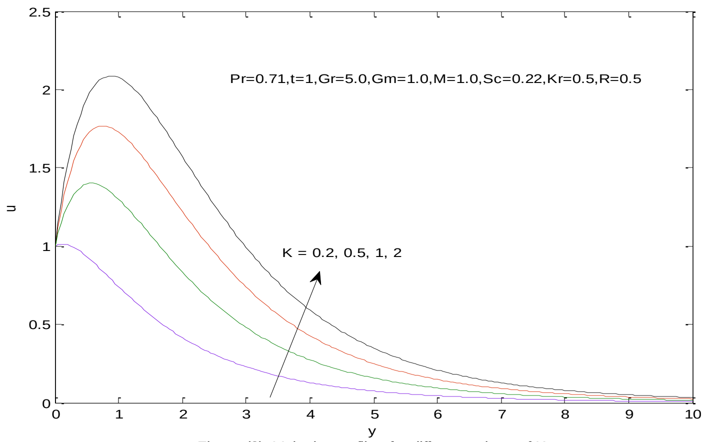

Figure (3): Velocity profiles for different values of K

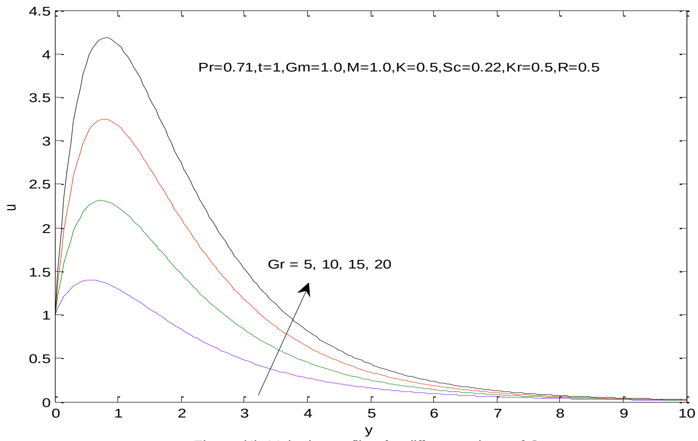

Figure (4): Velocity profiles for different values of Gr

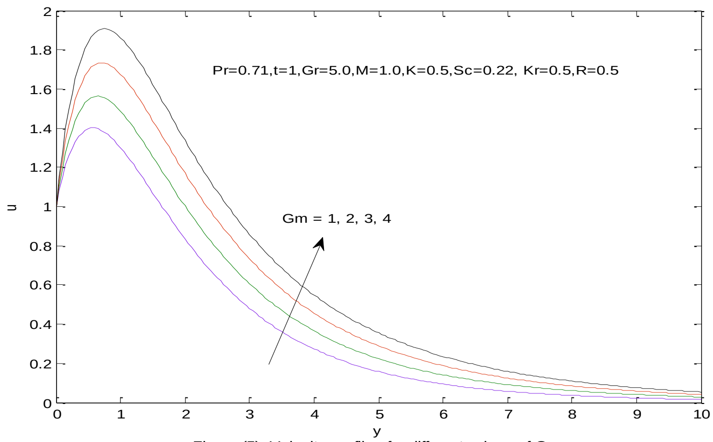

Figure (5): Velocity profiles for different values of Gm

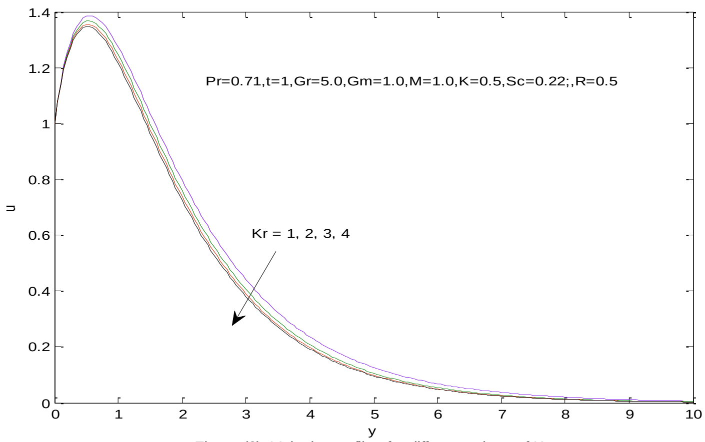

Figure (6): Velocity profiles for different values of Kr

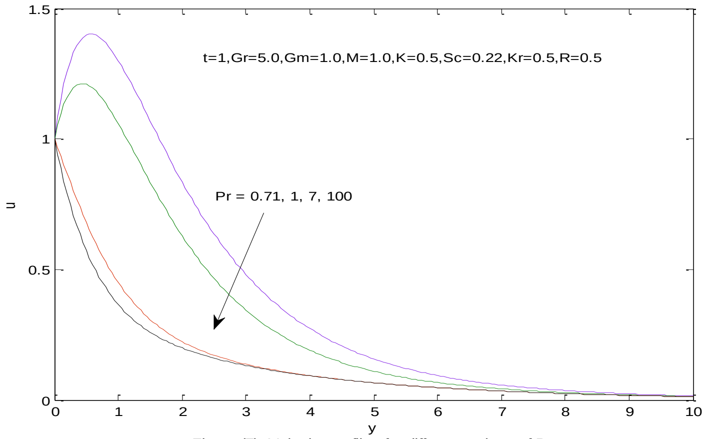

Figure (7): Velocity profiles for different values of Pr

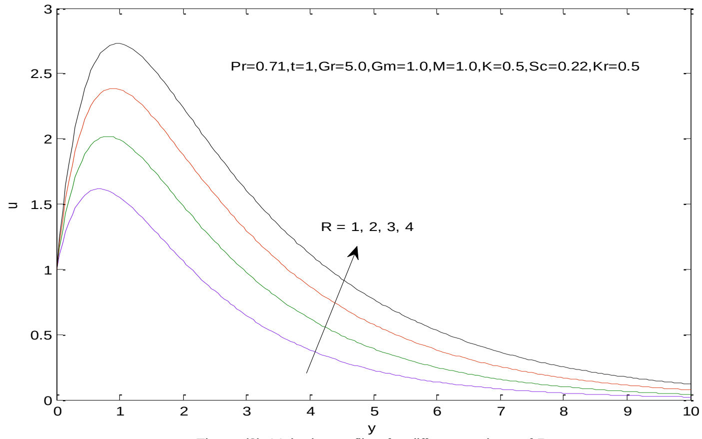

Figure (8): Velocity profiles for different values of R

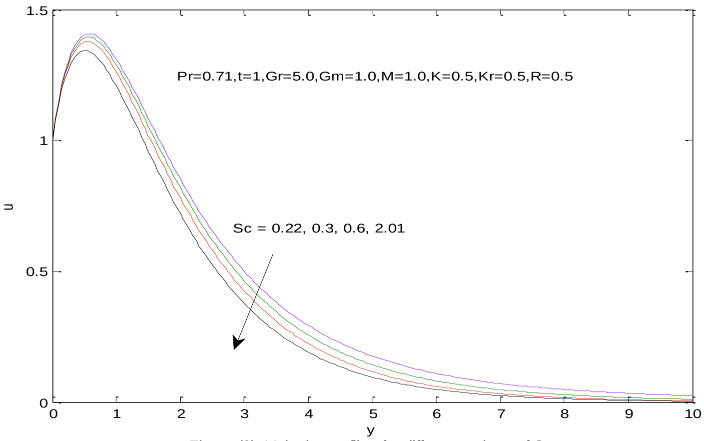

Figure (9): Velocity profiles for different values of Sc

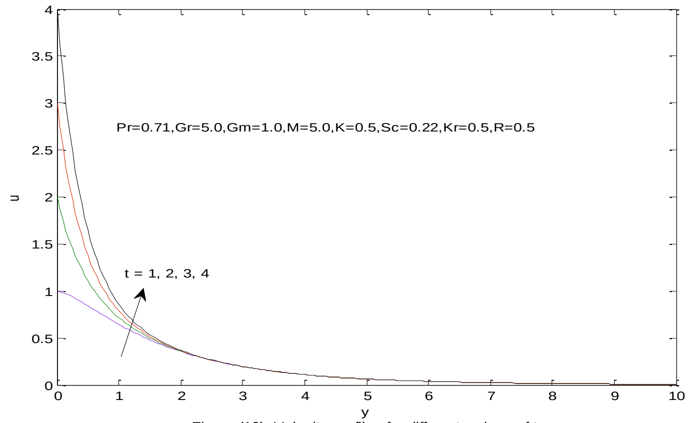

Figure (10): Velocity profiles for different values of t

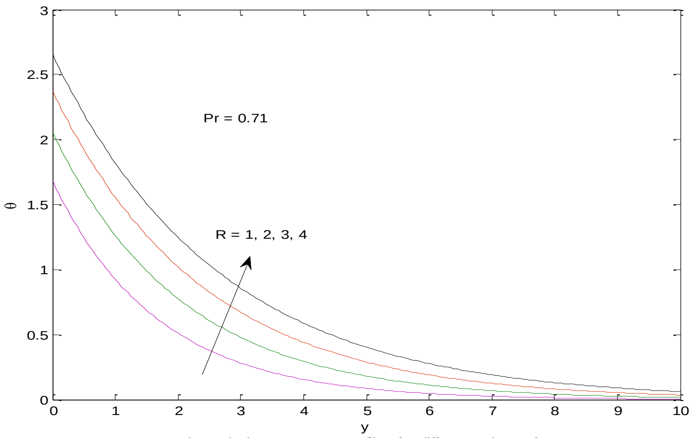

Figure (11): Temperatur profiles for different values of R

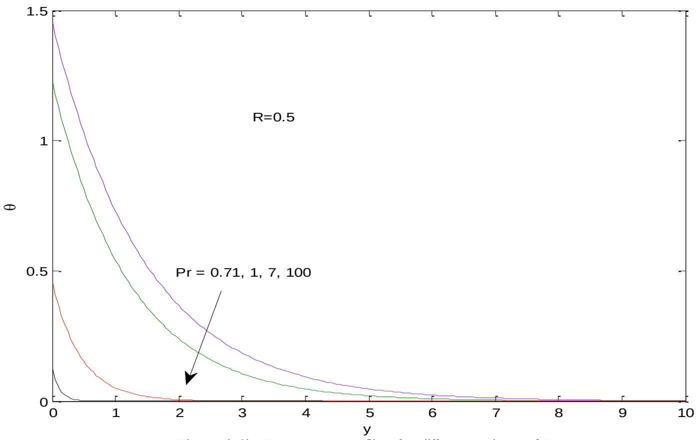

Figure (12): Temperatur profiles for different values of Pr

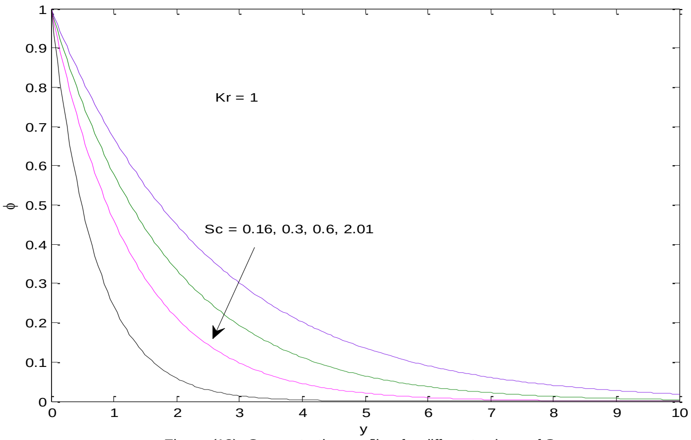

Figure (13): Concentration profiles for different values of Sc

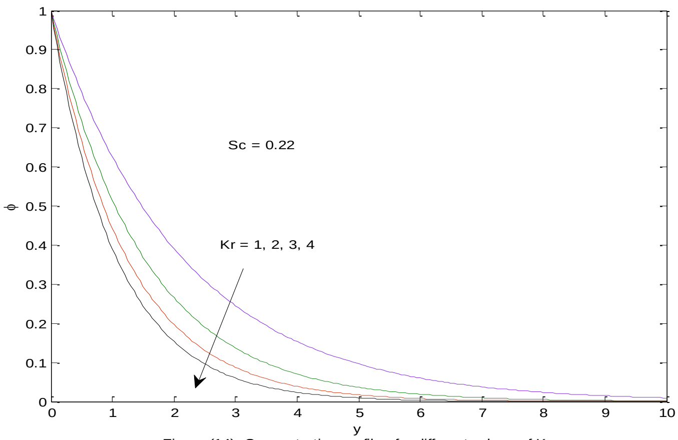

Figure (14): Concentration profiles for different values of Kr

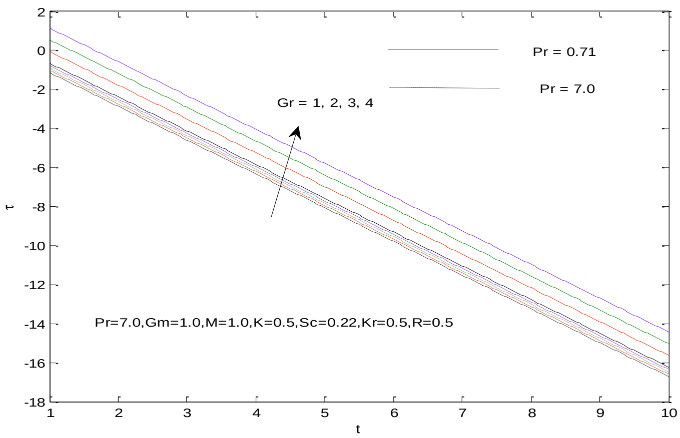

Figure (15): Skin friction for different values of Gr

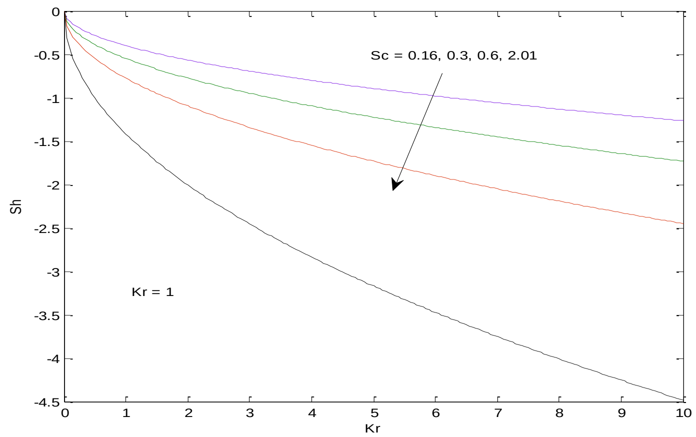

Figure (16): Sherwood number for different values of Sc

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