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Analytical solution of mass transfer effects on unsteady flow past an accelerated vertical porous plate with suction

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Abstract

This paper discussed the analytical solution of unsteady free convection and mass transfer flow past an accelerated infinite vertical porous flat plate with suction, heat generation and chemical species when the plate accelerates in its own plane. The governing equations are solved analytically using perturbation technique. The flow occurrence is described with the help of flow parameters such as porosity parameter (α), Grashof numbers (Grt, Grc), Hartmann's number (M), heat generation/absorption (β) and reaction parameter (γ). The effects of various parameters are discussed on flow variables and presented by graphs. A parametric study of all parameters involved was considered, and a representative set of results showing the effects of the control parameters were illustrated.

Keywords

unsteady, free convection, mass transfer, accelerated plate, porosity, suction, perturbation.

Mathematics Subject Classification: 76S05

1.0 Introduction

Free convection flows are of great interest in a number of industrial applications such as fibre and granular insulation, geothermal systems etc. Unsteady oscillatory free convective flows play an important role in chemical engineering, turbo machinery and aerospace technology such flows arise due to either unsteady motion of a boundary or boundary temperature. Besides, unsteadiness may also be due to oscillatory free stream velocity and temperature. In the past decades an intensive research effort has been devoted to problems on heat and mass transfer in view of their application to astrophysics, geophysics and engineering.

The study of convective flow with mass transfer along a vertical porous plate is receiving considerable attention of many researchers because of its varied applications in the field of cosmical and geophysical sciences. Permeable porous plates are used in the filtration processes and also for a heated body to keep its temperature constant and to make the heat insulation of the surface more effective. The study of stellar structure on the solar surface is connected with mass transfer phenomena.

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Its origin is attributed to difference in temperature caused by the non-homogeneous production of heat, which in many cases can rest not only in the formation of convective currents but also in violent explosions. Mass transfer certainly occurs within the mantle and cores of planets of the size of or larger than the earth. It is therefore interesting to investigate this phenomenon and to study in particular, the case of mass transfer on the free convection flow [1].

Flow past a vertical plate oscillating in its own plane has many industrial applications. The first exact solution of Navier-Stokes equation was given by Stokes [2] which is concerned with flow of viscous incompressible fluid past an horizontal plate oscillating in its own plane. Natural convection effects on Stokes problem was first studied by Soundalgekar [3]. The same problem was considered by Revankar [4] for an impulsively started or oscillating plate. Turbatu *et al* [5] investigated the flow of an incompressible viscous fluid past an infinite plate oscillating with increasing or decreasing velocity amplitude of oscillation. Recently, Gupta *et al.* [6] have analyzed flow in the Ekman layer on an oscillating plate. Soundalgekar *et al* [7] gave an exact solution for magnetic free convection flow past an oscillating plate. Mass transfer effects on flow past an oscillating plate considered by Lahurikar *et al* [8]. Of recent is the work of Okedoye et al [9], they report the numerical solution of heat and mass transfer in MHD flow in the presence of chemical reaction and Arrhenius heat generation of a stretched vertical permeable membrane.

Several workers have studied the problem of free convection flow with mass transfer, Okedoye [9] has a good review of some of this works.

The present study considers the unsteady free convection and mass transfer boundary layer flow past an accelerated infinite vertical porous flat plate with suction, heat generation and chemical species when the plate accelerates in its own plane. The governing equations are solved analytically using perturbation technique. The effects of the flow parameters on the velocity, temperature and the concentration distribution of the flow field are studied with the help of graphs and tables.

2.0 Formulation of the problem

Consider the unsteady flow of an incompressible viscous fluid past an accelerating vertical porous plate. Let the *x*-axis be directed upward along the plate and the *y*-axis normal to the plate. Let *u* and *v* be the velocity components along the *x*- and *y*- axes respectively. Let us assume that the plate is accelerating with a velocity $u = v_0$ in its own plane at time $t=0$. Then the unsteady boundary layer equations in the Boussinesq's approximation, together with Brinkman's empirical modification of Darcy's law, are

$$\frac{\partial v}{\partial y} = 0 \tag{2.1}$$

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \upsilon\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u - \frac{v}{A}u + \frac{g\beta_\tau}{\rho}\left(T - T_\infty\right) + \frac{g\beta_c}{\rho}\left(C - C_\infty\right) \tag{2.2}$$

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} + \frac{Q}{\rho c_p}\left(T - T_\infty\right) \tag{2.3}$$

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - R\left(C - C_\infty\right) \tag{2.4}$$

where k is the thermal diffusivity, υ is the kinematics viscosity, A is the permeability coefficient, β_τ is the volumetric expansion coefficient for heat transfer, β_c is the volumetric

expansion coefficient for mass transfer, ρ is the density, g is the acceleration due to gravity, T is the temperature, T_∞ is the temperature of the fluid far away from the plate, C is the concentration, C_∞ is the concentration far away from the plate and D is the molecular diffusivity.

On disregarding the Joulean heat dissipation, the boundary conditions are given by

$$\left.\begin{aligned} u = o,\ \ T = T_\infty,\ C = C_\infty\ \ for\ all\ \ y,\ t \le 0 \\ u = v_0,\ v = -v_0, T = T_w + \varepsilon e^{i\omega t},\ C = C_w + \varepsilon e^{i\omega t},\ y = 0,\ t > 0 \\ u = 0,\ T = T_\infty,\ C = C_\infty\ \ as\ \ y \to \infty,\ t > 0 \end{aligned}\right\} \quad (2.5)$$

From (2.1) using (2.5), we have $v(y) = -v_0$

Let us introduce the non-dimensional variables

$$\left.\begin{aligned} u' = \frac{u}{v_0},\ t' = \frac{tv_0^2}{4v},\ y' = \frac{yv_0}{v},\ A' = \frac{v_0^2}{v^2}, Q' = \frac{4Q\upsilon}{v_0^2} \\ \omega' = \frac{4\omega v}{v_0^2},\ \ \theta = \frac{T - T_\infty}{T_w - T_\infty},\ \ \phi = \frac{C - C_\infty}{C_w - C_\infty} \end{aligned}\right\} \quad (2.6)$$

where all the physical variables have their usual meanings.

With the help of (2.6) on dropping primes ($'$) the governing equations (2.2) – (2.4) with the boundary conditions reduce to

$$\frac{1}{4}\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\tau\theta + Grc\phi - \left(M + \frac{1}{\alpha}\right)u \quad (2.7)$$

$$\frac{\Pr}{4}\frac{\partial \theta}{\partial t} - \Pr\frac{\partial \theta}{\partial y} = \frac{\partial^2 \theta}{\partial y^2} + \Pr\beta\theta \quad (2.8)$$

$$\frac{Sc}{4}\frac{\partial \phi}{\partial t} - Sc\frac{\partial \phi}{\partial y} = \frac{\partial^2 \phi}{\partial y^2} - \gamma Sc\phi \quad (2.9)$$

$$\left.\begin{aligned} &u = 0,\ \ \theta = 0,\ \ \ \phi = 0,\ \ for\,all\ \ y,\ \ t \le 0 \\ &u = 1,\ \theta = 1 + \varepsilon e^{i\omega t},\ \ \ \phi = 1 + \varepsilon e^{i\omega t},\ y = 0,\ t > 0 \\ &u \to 0,\ \ \theta \to 0,\ \ \ \phi \to 0,\ as\ y \to \infty,\ \ t > 0 \end{aligned}\right\} \quad (2.10)$$

Where the parameters are as defined below:

$$\left.\begin{aligned} Gr\tau = \frac{g\beta_\tau(T_w - T_\infty)v}{v_0^3},\ \ Grc = \frac{g\beta_c(C_w - C_\infty)v}{v_0^3},\ \ M = \frac{\sigma B_0^2 v}{\rho v_0^2} \\ \alpha = \frac{v_0^2 A}{v^2},\ \Pr = \frac{\mu c_p}{k},\ \ \beta = \frac{Q\mu v}{kv_0^2\rho},\ \ Sc = \frac{v}{D},\ \ \gamma = \frac{Rv}{v_0^2} \end{aligned}\right\} \quad (2.11)$$

where *Pr, Sc , Grc, Grt,* α , β , γ and M are Prandtl number, Schmidt number, Grashof number for mass transfer, Grashof number for heat transfer, Porosity parameter, heat generation/absorption, Chemical reaction parameter and Hartmann's number.

3.0 Method of solution

To solve the problem posed in equations (2.1) – (2.4), we seek a perturbation series expansion in the limit of ε for our dependent variables. This is justified since ε is small; thus we write

$$\left.\begin{aligned} u(y,t) &= u_0(y) + \varepsilon e^{i\omega t} u_1(y) + o(\varepsilon^2) + \ldots \\ \theta(y,t) &= \theta_0(y) + \varepsilon e^{i\omega t} \theta_1(y) + o(\varepsilon^2) + \ldots \\ \mathrm{H}(y,t) &= \mathrm{H}_0(y) + \varepsilon e^{i\omega t} \mathrm{H}_1(y) + o(\varepsilon^2) + \ldots \end{aligned}\right\} \quad (3.1)$$

Using equation (3.1) equations (2.7), (2.8) and (2.9) on equating the harmonic and non – harmonic terms and neglecting the coefficient of ε^2, we obtain the equations governing the steady state motion and the equations governing the transient.

$$\frac{d^2\theta_0}{dy^2} + \Pr\frac{d\theta_0}{dy} - \Pr\beta\theta = 0 \qquad (3.2)$$

$$\theta_0(0) = 1, \ \theta_0(y) \to 0 \ \ as\ y \to \infty$$

$$\frac{d^2\phi_0}{dy^2} + Sc\frac{d\phi_0}{dy} - Sc\gamma\phi_0 = 0 \qquad (3.3)$$

$$\phi_0(y) = 1 \ at \ y = 0 \ \ \phi_0(y) \to 0 \ \ as\ y \to \infty$$

$$\frac{d^2u_0}{dy^2} + \frac{du_0}{dy} - \left(M^2 + \frac{1}{\alpha}\right)u_0 = -Gr\tau\theta_0 - Grc\phi_0 \qquad (3.4)$$

$$u_0(y) = 0 \ \ at\ y = 0, \ \ u_0(y) \to 0 \ \ as\ y \to \infty$$

and

$$\frac{d^2\theta_1}{dy^2} + \Pr\frac{d\theta_1}{dy} - \Pr\left(\frac{i\omega}{4} + \beta\right)\theta_1 = 0 \qquad (3.5)$$

$$\theta_1(y) = e^{i\omega t} \ at\ y = 0, \ \ \theta_1(y) \to 0 \ \ as\ y \to \infty$$

$$\frac{d^2\phi_1}{dy^2} + Sc\frac{d\phi_1}{dy} = Sc\left(\frac{i\omega}{4} + \gamma\right) \qquad (3.6)$$

$$\phi_1(y) = 1 \ \ at\ y = 0, \ \ \phi_1(y) \to 0 \ \ as\ y \to \infty$$

$$\frac{d^2u_1}{dy^2} + \frac{du_1}{dy} - \left(M^2 + \frac{1}{\alpha} + \frac{i\omega}{4}\right)u_1 = -Gr\tau\theta_1 - Grc\phi_1 \qquad (3.7)$$

$$u_1(y) = 0 \ \ at\ y = 0, \ \ u_1(y) \to 0 \ \ as\ y \to \infty$$

These sets of equations are now solved analytically for the velocity, concentration and the temperature fields. The solutions of equations (3.2) – (3.7) are

$$\phi_0(y)=e^{-ny},\ \theta_0(y)=e^{-my},\ u_0(y)=a_4 e^{-ry}+a_5 e^{-my}+a_6 e^{-ny}$$
$$\phi_1(y)=e^{-i\omega t}e^{-n_1 y},\ \theta_1(y)=e^{-i\omega t}e^{-m_1 y},\ u_1(y)=a_8 e^{-r_1 y}+a_9 e^{-m_1 y}+a_{10}e^{-n_1 y} \quad (3.8)$$

where

$$m=\frac{1}{2}\left(\Pr+\sqrt{\mathbf{Pr}^2-4\mathbf{Pr}\beta}\right),\ m_1=\frac{1}{2}\left(\Pr+\sqrt{\Pr^2-4\Pr\left(\beta-\frac{i\omega}{4}\right)}\right),$$

$$n=\frac{1}{2}\left(Sc+\sqrt{Sc^2+4Sc\gamma}\right),\ n_1=\frac{1}{2}\left(Sc+\sqrt{Sc^2+4Sc\left(\gamma+\frac{i\omega}{4}\right)}\right),$$

$$r=\frac{1}{2}\left(1+\sqrt{1+4\left(M+\frac{1}{\alpha}\right)}\right),\ r=\frac{1}{2}\left(1+\sqrt{1+4\left(M+\frac{1}{\alpha}+\frac{i\omega}{4}\right)}\right),$$

With

$$a_4=1-a_5-a_6,\quad a_8=-a_9-a_{10},\quad a_5=\frac{-Grt}{m^2-m-\left(M+\frac{1}{\alpha}\right)},\quad a_6=\frac{-Grc}{n^2-n-\left(M+\frac{1}{\alpha}\right)},$$

$$a_9=\frac{-Grt\cdot e^{i\omega t}}{m^2-m-\left(M+\frac{1}{\alpha}+\frac{i\omega}{4}\right)},\quad a_{10}=\frac{-Grc\cdot e^{i\omega t}}{n^2-n-\left(M+\frac{1}{\alpha}+\frac{i\omega}{4}\right)}$$

In equation (3.8), the functions $u_0(y)$, $\theta_0(y)$ and $\phi_0(y)$ are the mean velocity, the mean temperature and the mean concentration fields, respectively; and $u_1(y)$, $\theta_1(y)$ and $\phi_1(y)$ are, respectively, the velocity oscillatory part, the temperature oscillatory part and the concentration oscillatory part fields.

Now substituting equations (3.8) into equation (3.1), we obtain the required expressions for velocity, temperature and magnetic induction;

$$u(y,t)=a_4e^{-ry}+a_5e^{-my}+a_6e^{-ny}+\varepsilon e^{i\omega t}\left(a_8e^{-r_1y}+a_9e^{-m_1y}+a_{10}e^{-n_1y}\right) \quad (3.9)$$
$$\theta(y,t)=e^{-my}+\varepsilon e^{2i\omega t}e^{-m_1y} \quad (3.10)$$
$$\phi(y,t)=e^{-ny}+\varepsilon e^{2i\omega t}e^{-n_1y} \quad (3.11)$$

Having obtained expressions for velocity, temperature and concentration we then use a computer software package (Mapple 8.1 release) to build up the real and imaginary parts and their graphical representation is presented for analysis.

3.1 Skin-Friction

We now study skin-friction from velocity field. It is given by

$$c_f=\frac{T_f}{\rho u_\omega v_\omega}=\frac{d^2}{dy^2}u(y,t)\bigg|_{y=0},\quad \tau_f=\mu\frac{du}{dy}\bigg|_{y=0}$$

which reduces to $c_f = \left(\frac{\partial u}{\partial y}\right)_{y=0}$. Therefore

$$c_f = -a_4 r - a_5 m - a_6 n + \varepsilon e^{2i\omega t}\left(-a_8 r_1 - a_9 m_1 - a_{10} n_1\right) \qquad (3.12)$$

3.2 Nusselt Number

In non-dimensional form, the rate of heat transfer at the wall is computed from Fourier's law and is given by

$$Nu = \frac{q_\omega v}{(T_\omega - T_\infty)Kv_\omega} = \frac{-d}{dy}\theta(y\,t)\bigg|_{y=0}, \quad q_\omega = -K\frac{dT}{dy}\bigg|_{y=0},$$

Therefore,
$$Nu = -m - \varepsilon m_1 e^{2i\omega t} \qquad (3.13)$$

3.3 **Sherwood Number**

The rate of mass transfer at the wall which is the ratio of length scale to the diffusive boundary layer thickness is given by

$$Sh = \frac{J_\omega\, v}{(c_\omega - c_\infty)D\,v_\omega} = -\frac{d}{dy}\phi(y,t)\bigg|_{y=0}, \quad J_\omega = -D\frac{d\phi}{dy}\bigg|_{y=0}$$

which implies
$$Sh = -n - \varepsilon n_1 e^{2i\omega t} \qquad (3.14)$$

4.0 Discussions and results

The problem of unsteady heat and mass transfer flow past an accelerated infinite vertical porous flat plate with heat generation/absorption, chemical reaction and suction has been formulated, analyzed and solved analytically by asymptotic expansions. In order to point out the effects of various parameters on flow characteristic, the following discussion is set out. The value of the Prandtl number is chosen Pr = 0.71 (plasma). The values of the Schmidt number is chosen to represent the presence of species by water vapour (0.60). All other parameters are primarily chosen as follows: $Gr\tau = 10$, $Grc = 5$, $\alpha = 3$, $\beta = 0.1775$, $M = 0.5$, $\gamma = -0.15$, $\omega t = 2\pi$, $t = 0.25$, unless otherwise stated. We displayed the effect of each flow parameters on the concentration, temperature and velocity distribution of the flow field with the help of concentration profile (Figure (4.1)), temperature profile (Figure (4.2)) and velocity profiles (Figures (4.3) - (4.8)). It should be noted that $Grt > 0$ and $Grt < 0$ represent cooling of the plate and heating of the plate respectively. Also $\gamma < 0$, $\gamma = 0$ and $\gamma > 0$ represent generative, no and destructive chemical reactions respectively. While $\beta < 0$, $\beta = 0$ and $\beta > 0$ indicates heat generation, no heat generation/absorption and heat absorption respectively.

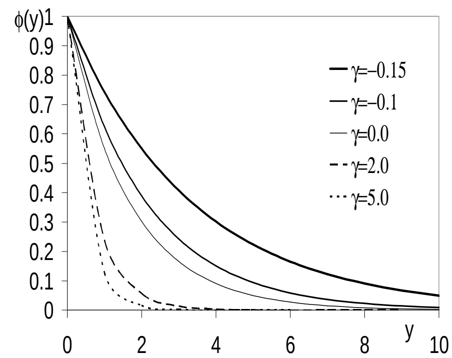


Figure 4.1: Variation of concentration for various values of γ

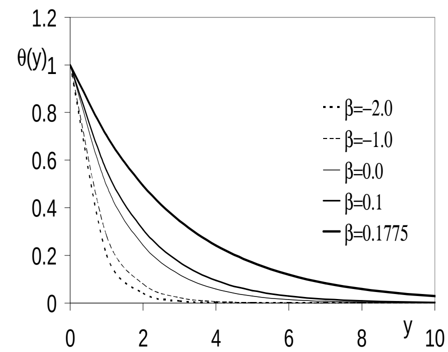


Figure 4.2: Variation of temperature for various values of β

4.1 Concentration distribution

The concentration distribution of the flow field in presence of foreign species, such as water vapour (Sc = 0.60) is shown in Figures (4.1). It is affected by two flow parameters, namely Schmidt number (Sc) and chemical reaction parameter (γ). In our analysis here, the value of Schmidt number is taken to be 0.60, thus the only parameters that affect the concentration distribution is γ. The concentration distribution is vastly affected by the presence of foreign species in the flow field. A comparative study of the curves of figure 4.1 shows that the concentration distribution of the flow field decreases faster as the reaction parameter (γ) becomes larger. The concentration boundary layers increase with generative chemical reaction and decreases with destructive chemical reaction. Thus greater chemical reaction parameter (destructive reaction) leads to a faster decrease in concentration of the flow field.

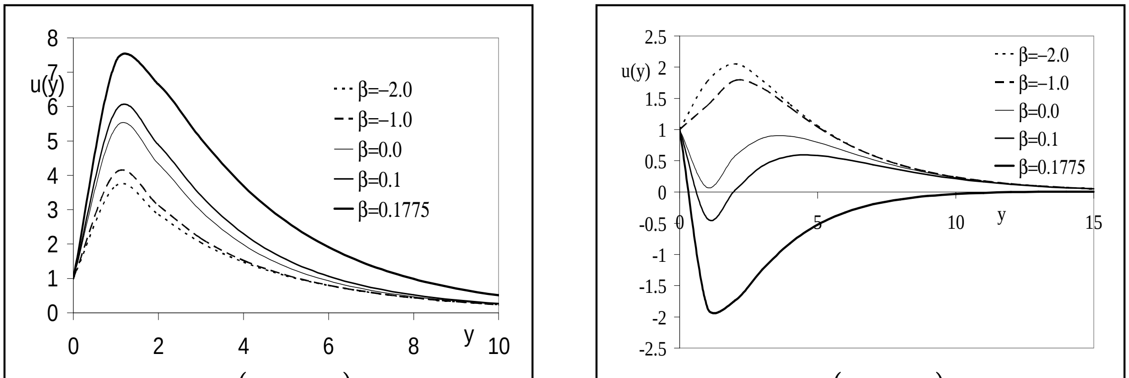
4.2 Temperature field

The temperature of the flow field is mainly affected by two flow parameters, namely, heat generation/absorption β and the Prandtl number (Pr). The effects of β on temperature of the flow field are shown in Figure (4,2). The figure shows that increase in heat absorption increases the temperature field while increase in heat generation lowers the temperature field. In other words, cooling of the plate is faster as the heat generation parameter becomes larger. Thus it may be concluded that heat generation leads to faster cooling of the plate.

4.3. Velocity field

The velocity of the flow field is found to change more or less with the variation of the flow parameters. The effect of the flow parameters on the velocity field is analyzed with the help of Figures (4.3) - (4.8).

Figures (4.3a) – (4.7a) displayed the case of cooling of the plate, while Figures (4.3b – 4.7(b) is for the case of heating of the plate, while the variation of velocity with thermal buoyancy is displayed in Figure 4.8.



4.3(a) Case $(Grt > 0)$ cooling

4.3(b) Case $(Grt < 0)$ heating

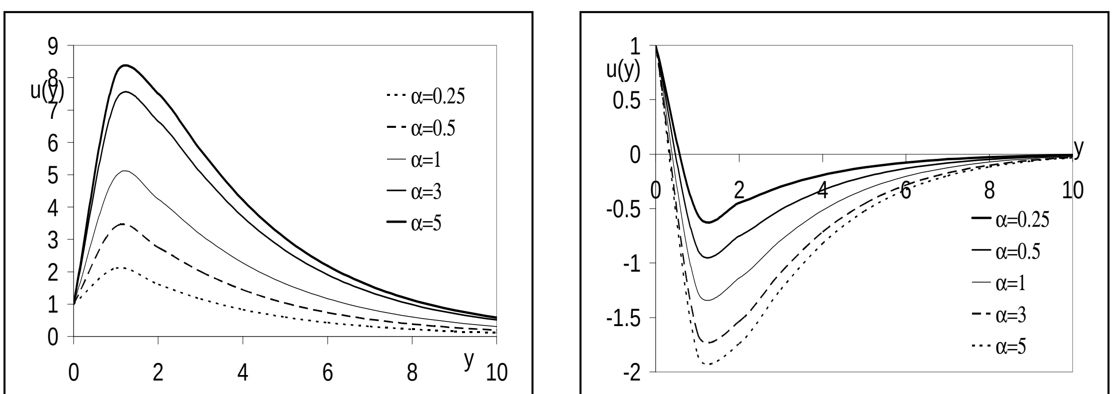
Figure 4.3: Velocity profile for various values of β

4.3.1. Effect of heat generation/absorption (β)

Figure (4.3) shows the velocity profiles against *y* for several values of the heat generation/absorption (β). For the case of cooling of surface, increase in heat generation $(\beta < 0)$ is found to retard the velocity of the flow field, while increase in heat absorption $(\beta > 0)$ brings about an increase in velocity of the flow field (Figure (4.3a)). One interesting inference of this finding is that maximum velocity occurs in the body of the fluid close to the surface and not the surface. On the other hand, the reverse is the case for heating of the surface (Figure (4.3b)). In fact, maximum in the velocity field only occurs during heat generation and for heat absorption the velocity is maximum at the surface.

4.3.2 Effect of porosity parameter (α)

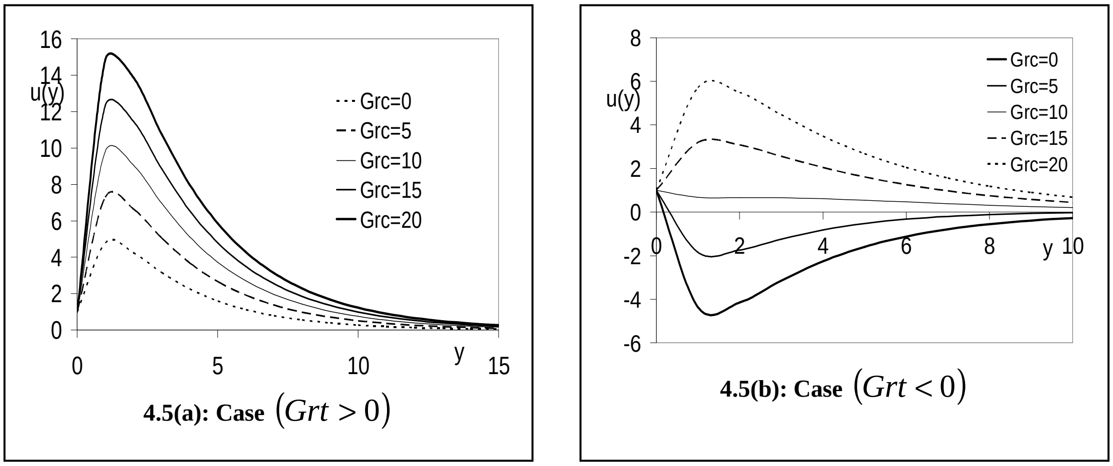
Figure (4.4) depicts the effect of porosity parameter **(α)** on the velocity of the flow field. Here, we discovered that during cooling of the surface, velocity increases as porosity increases.



4.4(a) Case $(Grt > 0)$

4.4(b) Case $(Grt < 0)$

Figure 4.4: Velocity profile for various values of α



4.5(a): Case $(Grt > 0)$ **4.5(b): Case** $(Grt < 0)$

Figure 4.5: Variation of velocity for various values of Grc

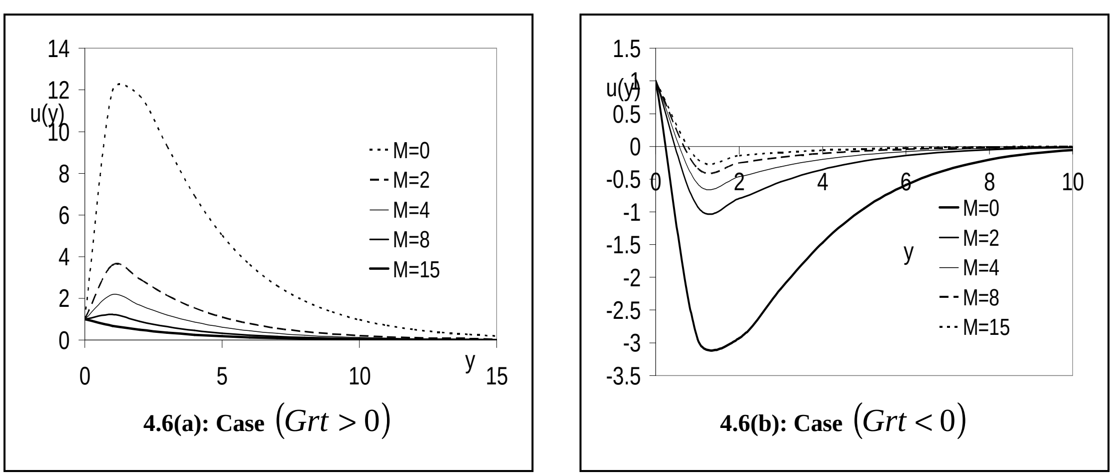
This is because the presence of foreign gases has the tendency to increase thermal and mass buoyancy. The porosity parameter is found to decelerate the velocity of the flow field for the case of heating of the surface. That is as against cooling of surface, heating of surface results in reverse flow and the higher the porosity parameter , the more is the reduction in velocity.

4.3.3 Effect of mass Grashof number (Grc)

The effects of Grashof number for mass transfer (*Grc*) on the velocity of the flow field is presented in Figure (4.5). A study of the curves of the figure (4.5a) and 4.5(b) shows that the Grashof number for mass transfer accelerate the velocity of the flow field. Comparing the curves of Figure (4.5), it is further observed that the increase in velocity of the flow is more pronounced with higher mass Grashof number both in cooling and heating of surface. In case of heating of the plate, maximum velocity is on the surface for lower values of *Grc* whereas, it is near the surface for higher values of *Grc*.

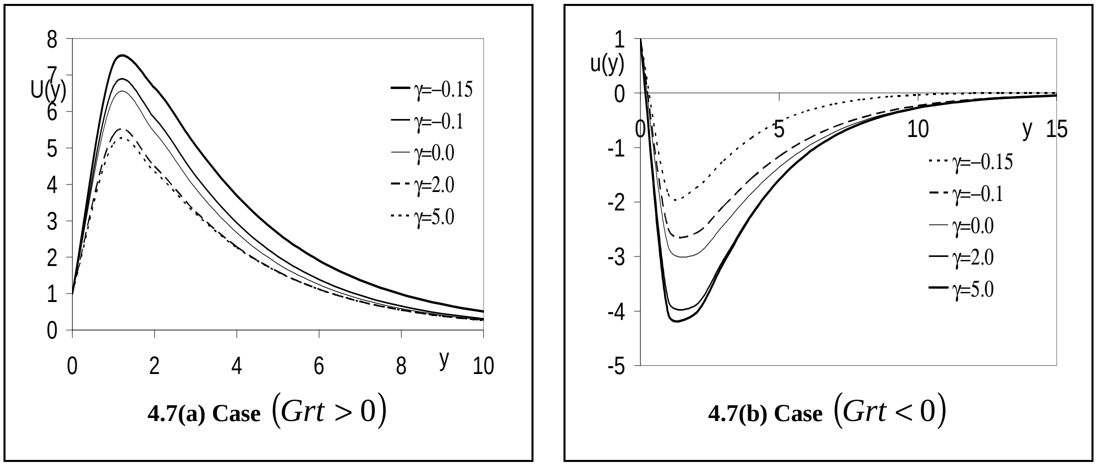
4.3.4 Effect of Hartmann's number(*M*)

In the case of cooling of the plate, it is found that the flow field suffers a decrease in velocity as *M* increases (4.6(a)). It is because the application of transverse magnetic field will result in a resistive type of force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity. The highest velocity is attain when this resistive type of force is zero, that is *M=0.* The reverse is the case in heating of the plate (4.6(b)).



4.6(a): Case $(Grt > 0)$ **4.6(b): Case** $(Grt < 0)$

Figure 4.6: Variation of velocity for various values of *M*



4.7(a) Case $(Grt > 0)$ **4.7(b) Case** $(Grt < 0)$

Figure 4.7: Variation of velocity for various values of γ

4.3.5 Effect of reaction parameter (γ)

Figure (4.7) depicts the velocity profiles against y for various values of reaction parameter. Reaction parameter is found to decrease the velocity of the flow for cooling of the plate. It could be seen from figure (4.7(a)) that maximum velocity field occurs during generative chemical reaction $\gamma < 0,$ and reduces during destructive chemical reaction. In the case of heating of the plate (Figure 4.7(b)), the maximum velocity is the surface velocity, while as in the case cooling of the plate, reaction parameter decreases the velocity of the flow field.

4.3.5 Effect of Grashof number for heat transfer (Grt)

The effect of thermal Grashof number on the velocity of the flow field is presented in Figure (4.8). In the figure, we show that the Grashof number for heat transfer (*Grt*) accelerate the velocity of the flow field. Comparing the curves of Figure (4.3), it is further observed that the increase in velocity of the flow field is more significant in presence higher thermal buoyancy. Thus, heat transfer has a dominant effect on the flow field.

4.4. Heat flux, Rate of mass transfer and Skin-friction

The heat flux in terms of Nusselt number (*Nu*), rate of mass transfer in terms of Sherwood number *(Sh)* and the non-dimensional skin friction (c_f)) are entered in tables (4.1) and (4.2) for different values of porosity parameter (α) reaction parameter, heat generation/absorption, Hartmann's number and heat and mass Grashof numbers.

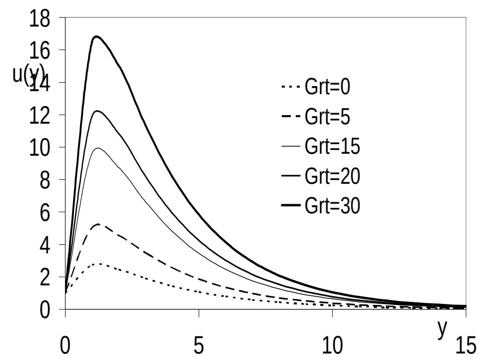


Figure 4.8: Variation of velocity for various values of Grt

4.4.1 Effect of control parameters on skin friction.

Table (4.1) shows the effect of α, γ, β, *M, Grt* and *Grc* on the flow field. It was shown from the table that an increase in the value(s) of α, β, *Grt* and *Grc* result in an increase in the Shear stress. The reverse is the case for γ and *M*, c_f reduces as these parameters increases. Also, skin – friction is higher for generative chemical reaction and lower for heat generation when compared with heat absorption case.

Table 4.1: Effect of the flow control parameters on Skin – Friction c_f

α	γ	β	M	Grt	Grc	c_f		α	γ	β	M	Grt	Grc	c_f
0.25	-0.15	0.18	0.5	10	5	4.81680		3	-0.15	0.18	0.5	10	0	-0.5092
0.5	-0.15	0.18	0.5	10	5	7.9437		3	-0.15	0.18	0.5	10	5	1.1421
1	-0.15	0.18	0.5	10	5	11.1921		3	-0.15	0.18	0.5	10	10	2.7935
2	-0.15	0.18	0.5	10	5	14.1811		3	-0.15	0.18	0.5	10	15	4.4448
3	-0.15	0.18	0.5	10	5	15.6448		3	-0.15	0.18	0.5	10	20	6.0962
4	-0.15	0.18	0.5	10	5	16.5226		3	-0.15	0.18	0.5	10	25	7.7476
8	-0.15	0.18	0.5	10	5	18.0920		3	-0.15	0.18	0.5	10	30	9.3989
3	-0.15	0.18	0	10	5	23.8428		3	-0.15	0.18	0.5	10	5	15.6448
3	-0.15	0.18	0.5	10	5	15.6448		3	-0.1	0.18	0.5	10	5	14.6293
3	-0.15	0.18	1	10	5	12.0219		3	0	0.18	0.5	10	5	14.0814
3	-0.15	0.18	1.5	10	5	9.8498		3	1	0.18	0.5	10	5	12.6884
3	-0.15	0.18	2	10	5	8.3508		3	2	0.18	0.5	10	5	12.2242
3	-0.15	0.18	2.5	10	5	7.2284		3	3	0.18	0.5	10	5	11.9494
3	-0.15	0.18	3	10	5	6.3419		3	4	0.18	0.5	10	5	11.7584
3	-0.15	0.18	0.5	0	5	-2.1018		3	-0.15	-8	0.5	10	5	7.4868
3	-0.15	0.18	0.5	5	5	-0.4799		3	-0.15	-4	0.5	10	5	8.2879
3	-0.15	0.18	0.5	10	5	1.1421		3	-0.15	-2	0.5	10	5	9.1492
3	-0.15	0.18	0.5	15	5	2.7641		3	-0.15	-1	0.5	10	5	10.0036
3	-0.15	0.18	0.5	20	5	4.3861		3	-0.15	0	0.5	10	5	12.4775
3	-0.15	0.18	0.5	25	5	6.0081		3	-0.15	0.1	0.5	10	5	13.3290
3	-0.15	0.18	0.5	30	5	7.6300		3	-0.15	0.18	0.5	10	5	15.6452

4.4.2 Effect of heat generation and chemical reaction on heat flux and mass transfer.

Heat flux at the wall is controlled by heat generation/absorption coefficient β, while Sherwood number is controlled by reaction parameter γ. In table (4.2), we discovered that rate of mass transfer at the wall increases as destructive chemical reaction increases and reduce as generative chemical reaction increases. The effect of heat generation on rate of heat transfer is more pronounced compared to heat absorption. Nusselt number increases as heat generation increases and reduce as heat absorption increases.

Table 4.2: Effect of γ and β on *Sh* and *Nu* number respectively

γ	*Sh*		β	*Nu*
-0.15	0.307832		-8	2.792237
-0.1	0.481193		-4	2.098054
0	0.608316		-2	1.614563
1	1.142383		-1	1.282474
2	1.450311		0	0.719433
3	1.691617		0.1	0.598646
4	1.896815		0.1775	0.363805

5.0 Conclusions

The above study brings out the following inferences of physical interest on the velocity, temperature and concentration distribution of the flow field.

(1) The concentration boundary layers increase with generative chemical reaction and decreases with destructive chemical reaction.

(2) Heat generation leads to faster cooling of the plate.

(3) For the case of cooling of surface, increase in heat generation ($\beta < 0$) is found to retard the velocity of the flow field, while increase in heat absorption ($\beta > 0$) brings about an increase in velocity of the flow field.

(4) The porosity parameter decelerates the velocity of the flow field for the case of heating of the surface.

(5) Grashof numbers for mass and heat transfer accelerate the velocity of the flow field. In case of heating of the plate, maximum velocity is on the surface for lower values of *Grc* whereas, it is near the surface for higher values of *Grc*.

(6) The flow field suffers a decrease in velocity as Hartmann's number *M* increases

(7) Increase in reaction parameter (destructive reaction) decrease the velocity of the flow for cooling of the plate.

(8) Rate of mass transfer at the wall increases as destructive chemical reaction increases and reduce as generative chemical reaction increases.

(9) Nusselt number increases as heat generation increases and reduce as heat absorption increases.

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