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Finite difference analysis of hydromagnetic mixed convective mass diffusion boundary layer flow past an accelerated vertical porous plate through a porous medium with suction

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Abstract
This paper focuses on the unsteady hydromagnetic mixed convective heat and mass transfer boundary layer flow of a viscous incompressible electrically conducting fluid past an accelerated infinite vertical porous flat plate in a porous medium with suction in presence of foreign species such as H_2, He, H_2O vapour and NH_3. The governing equations are solved both analytically and numerically using error function and finite difference scheme. The flow phenomenon has been characterized with the help of flow parameters such as magnetic parameter (M), suction parameter (a), permeability parameter (K_p), Grashof number for heat and mass transfer (G_r, G_c), Schmidt number (S_c) and Prandtl number (P_r). The effects of the above parameters on the fluid velocity, temperature, concentration distribution, skin friction and heat flux have been analyzed and the results are presented graphically and discussed quantitatively for Grashof number $G_r>0$ corresponding to cooling of the plate. It is observed that a growing magnetic parameter (M) retards the velocity of the flow field at all points and a greater suction leads to a faster reduction in the velocity of the flow field. Further, as we increase the permeability parameter (K_p) and the Grashof numbers for heat and mass transfer (G_r, G_c) the velocity of the flow field enhances at all points, while a greater suction/Prandtl number leads to a faster cooling of the plate. It is also observed that a more diffusive species has a significant decrease in the concentration boundary layer of the flow field and a growing suction parameter enhances both skin friction (τ') and heat flux (N_u) at the wall corresponding to cooling of the plate ($G_r>0$).

Keywords: Hydromagnetic; Mixed convection; Mass diffusion; Accelerated plate; Suction; Porous medium.

1. Introduction
The phenomenon of mixed convective flow with mass diffusion has been a subject of interest of many researchers because of its varied applications in natural sciences, engineering sciences and also in

industry. Such phenomena are observed in buoyancy induced motions in the atmosphere, in bodies of water, quasi-solid bodies such as earth, etc.. Mixed convective flows with mass transfer through porous media play an important role in chemical engineering, turbo-machinery and in aerospace technology. Such flows arise either due to unsteady motion of boundary or boundary temperature. In natural processes and industrial applications many transport processes exist where transfer of heat and mass takes place simultaneously as a result of combined buoyancy effects of thermal diffusion and diffusion of chemical species. The phenomenon of heat and mass transfer is also very common in chemical process industries such as food processing and polymer production. Some of the findings of this study include applications to nuclear research and in the study of stars and planets.

In view of these applications a series of investigations were made to study the flow past a vertical wall. Brinkman [1] estimated the viscous force imparted by a flowing fluid in a dense swarm of particles. Hasimoto [2] analyzed the boundary layer growth on a flat plate with suction or injection. Soundalgekar and Haldavnekar [3] have discussed the MHD free convective flow in a vertical channel. Soundalgekar [4] has shown the effect of free convection on steady MHD flow past a vertical porous plate. Yamamoto and Iwamura [5] have investigated the problem of flow with convective acceleration through a porous medium. Raptis and his associates [6] have analyzed the unsteady free convective flow through a porous medium adjacent to a semi-infinite vertical plate using finite difference scheme. Singh and Sacheti [7] have discussed the unsteady hydromagnetic free convection flow with constant heat flux employing the same method. Singh and Soundalgekar [8] analyzed the transient free convection effect in cold water past an infinite vertical porous plate.

Mansutti and his co-workers [9] have studied the steady flows of non-Newtonian fluids past a porous plate with suction or injection. Chandran *et al*. [10] studied the unsteady hydromagnetic free convection flow with heat flux and accelerated boundary motion. Jha [11] studied the effects of magnetic field on the transient free convective flow in a vertical channel. Acharya and his associates [12] have investigated the heat and mass transfer effects on the flow of a viscous fluid over an accelerating surface in presence of suction and blowing. Dash and Das [13] have analyzed the effect of Hall current on MHD flow along an accelerated porous flat plate with mass transfer and internal heat generation. Choudhury and Das [14] discussed the magnetohydrodynamic boundary layer flows of non-Newtonian fluid past a flat plate. Kim [15] reported the unsteady MHD heat transfer flow past a semi-infinite vertical porous moving plate with variable suction. Sharma and Pareek [16] have discussed the steady free convective MHD flow past a vertical porous moving surface.

Singh and Thakur [17] have given an exact solution of plane unsteady MHD non-Newtonian fluid flows. Makinde *et al*. [18] have investigated the un- steady free convection flow with suction on an accelerating porous plate. Das and his co-workers [19] have discussed the hydromagnetic flow and heat transfer of an elastico-viscous fluid between two horizontal porous plates by finite difference method. Pathal *et al*. [20] analyzed the unsteady mass, momentum and heat transfer in MHD free convection flow along a vertical plate suddenly set in motion. Sarangi and Jose [21] studied the unsteady free convective MHD flow and mass transfer past a vertical porous plate with variable temperature. Recently, Das and his team [22] solved numerically the mass transfer effects on unsteady flow past an accelerated vertical porous plate with suction. More recently, Das and his associates [23] discussed the magnetohydrodynamic flow and heat transfer in a viscous incompressible fluid between two parallel porous plates employing finite difference scheme.

The objective of the proposed work is to analyze the unsteady mixed convective heat and mass transfer boundary layer flow of a viscous incompressible electrically conducting fluid past an accelerated infinite vertical porous flat plate in a porous medium with suction in presence of foreign species such as H_2, He, H_2O vapour and NH_3 and a transverse magnetic field. The governing equations are solved both analytically and numerically using error function and finite difference scheme. The flow phenomenon has been characterized with the help of flow parameters and the effects of these parameters on the velocity field, temperature field, concentration distribution, skin friction and heat flux have been analyzed and the results are presented graphically and discussed quantitatively with the help of graphs and tables for Grashof number $G_r>0$ corresponding to cooling of the plate.

2. Formulation of the problem

Consider the unsteady mixed convective mass transfer boundary layer flow of a viscous incompressible electrically conducting fluid past an accelerating vertical infinite porous flat plate in a porous medium in presence of foreign species such as H_2, He, H_2O vapour and NH_3 and a transverse magnetic field B_0. 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 x- and y- axes respectively. We assume that the plate is accelerating with a velocity u = Ut in its own plane at time $t \geq 0$. Then the unsteady mixed convective boundary layer equations under usual Boussinesq's approximation, together with Brinkman's [1] empirical modification of Darcy's law are

$$\frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \mu\frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) - \frac{\mu}{k^*}u - \frac{\sigma B_0^2}{\rho}u \tag{2}$$

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y} = k\frac{\partial^2 T}{\partial y^2} \tag{3}$$

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2}, \tag{4}$$

where μ is the kinematic viscosity, k is the thermal diffusivity, k^* is the permeability coefficient, β is the volumetric coefficient of expansion for heat transfer, β^* is the volumetric coefficient of expansion for mass transfer, ρ is the density, σ is the electrical conductivity of the fluid , 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 of the fluid far away from the plate and D is the molecular diffusivity.

The necessary boundary conditions are,

$$\begin{aligned} &u = Ut\ ,\ T = T_w\ ,\ C = C_w\ ,\ y = 0, \\ &u \to 0\ ,\ T \to T_\infty\ ,\ C \to C_\infty\ \text{ as }\ y \to \infty\ \text{ for }\ t \to \infty \end{aligned} \tag{5}$$

We introduce the similarity variables and dimensionless quantities

$$\begin{aligned} &\eta = \frac{y}{2\sqrt{\mu t}}\ ,\ u = Utf(\eta)\ ,\ \theta = \frac{T - T_\infty}{T_w - T_\infty}, C = \frac{C - C_\infty}{C_w - C_\infty}, M = \frac{\sigma B_0^2}{\rho}\frac{\mu}{v^2}, \\ &K_p = \frac{v^2 k^*}{\mu^2}\ ,\ P_r = \frac{\mu}{k}\ ,\ S_c = \frac{\mu}{D}\ ,\ G_r = 4g\beta\frac{(T_w - T_\infty)}{U}, G_c = 4g\beta^*\frac{(C_w - C_\infty)}{U} \end{aligned} \tag{6}$$

where: P_r = Prandtl number, G_r= Grashof number for heat transfer, G_c= Grashof number for mass transfer, K_p= permeability parameter, M = magnetic parameter, S_c= Schmidt number. and the primes denote the derivative with respect to η.

Following Hasimoto [2], Singh and Soundalgekar [8], we choose

$$v = -a\left(\frac{\mu}{t}\right)^{\frac{1}{2}} \tag{7}$$

where a > 0, the suction parameter. Using equations (6) and (7), equations (2) - (4) become

$$f'' + 2(\eta + a)f' - 4\left\{1 + a^2\left(M + \frac{1}{K_p}\right)\right\}f = -G_r\theta - G_cC \tag{8}$$

$$\theta'' + 2(\eta + a)P_r\theta' = 0 \tag{9}$$

$$C'' + 2(\eta + a)S_cC' = 0 \tag{10}$$

The boundary conditions now take the form

$$f(0)=1,\ \ \theta(0)=1,\ \ C(0) = 1,\ \ f(\infty) = 0,\ \ \theta(\infty) = 0,\ \ C(\infty) = 0 \tag{11}$$

2.1 Skin friction
The skin friction at the wall is given by

$$\tau = \rho\mu\left(\frac{\partial u}{\partial y}\right) = -\frac{\rho U}{2}\sqrt{\mu t}\ f'(0) \tag{12}$$

In non-dimensional form, we get

$$\tau' = \frac{2\tau}{\rho U\sqrt{\mu t}} = -f'(0) \tag{13}$$

2.2 Heat transfer
The non-dimensional local heat flux at the plate in terms of Nusselt number (N_u) is given by

$$N_u = \frac{2q_w\sqrt{\mu t}}{k(T_w - T_\infty)} = -\theta'(0) \tag{14}$$

where q_w is the heat flux per unit area.

3. Method of solution
Solving equations (9) and (10) exactly by error function subject to boundary conditions (11), we get

$$\theta = \frac{\operatorname{erfc}\left((\eta + a)\sqrt{P_r}\right)}{\operatorname{erfc}\left(a\sqrt{P_r}\right)} \tag{15}$$

$$C = \frac{\operatorname{erfc}\left((\eta + a)\sqrt{S_c}\right)}{\operatorname{erfc}\left(a\sqrt{S_c}\right)} \tag{16}$$

Equation (8) is solved numerically using finite difference scheme. In order to solve equation (8), we set up the following difference approximations:

$$f' = \frac{f_{i+1} - f_{i-1}}{2h},\ \ f'' = \frac{f_{i+1} - 2f_i + f_{i-1}}{h^2} \tag{17}$$

Introducing these difference approximations (17) in equation (8), we obtain

$$A_1 f_{i+1} + A_2 f_i + A_3 f_{i-1} = B_1 + B_2 \tag{18}$$

where: $A_1 = \dfrac{1+h(\eta_i + a)}{h^2}$, $A_2 = -\dfrac{2+4h^2\left\{1+a^2\left(M+\dfrac{1}{K_p}\right)\right\}}{h^2}$, $A_3 = \dfrac{1-h(\eta_i + a)}{h^2}$

$$B_1 = -G_r\theta_i, \quad B_2 = -G_c C_i \tag{19}$$

$$\eta_i = ih \;,\; h = \frac{L}{N+1} \;,\; 0 \le \eta_i \le L \tag{20}$$

We choose L = 2.0 and N = 200, since it lies well outside the boundary layer.

4. Discussions and results

The problem of hydromagnetic unsteady mixed convective mass transfer boundary layer flow past an accelerated infinite vertical porous flat plate in a porous medium with suction in presence of foreign species such as H_2, He, H_2O vapour and NH_3 has been formulated, analyzed and solved both analytically and numerically using error function and finite difference scheme. The effects of the flow parameters such as magnetic parameter (M), suction parameter (a), permeability parameter (K_p), Grashof numbers for heat and mass transfer (G_r, G_c), Schmidt number (S_c) and Prandtl number (P_r) on the velocity, temperature and concentration profiles of the flow field are presented with the help of velocity profiles (Figures 1-5), temperature profiles (Figures 6, 7) and concentration profiles (Figures 8, 9). The non-dimensional skin friction at the wall and the local heat flux in terms of Nusselt number are also discussed and entered in Table 1. The results obtained are discussed for Grashof number G_r>0 corresponding to cooling of the plate.

4.1 Velocity field

The velocity of the flow field varies more or less with the variation of the flow parameters. The major flow parameters affecting the velocity of the flow field are magnetic parameter (M), suction parameter (a), permeability parameter (K_p), Grashof numbers for heat and mass transfer (G_r, G_c). The effects of these parameters on the velocity of the flow field in presence of H_2, a lighter diffusive species (S_c=0.22) are analyzed with the help of Figures 1-5. The velocity profiles of the flow field closely agree with the results obtained in case of Makinde *et al*. [18] and Das *et al*. [22].

4.1.1 Effect of magnetic parameter (M)

Figure 1 depicts the effects of magnetic parameter (M) on the velocity of the flow field. Keeping other parameters of the flow field constant, the magnetic parameter is varied and its effect is studied. Curve with M=0 corresponds to flow in absence of magnetic field (non-MHD flow) and the other curves represent flow in presence of magnetic field (MHD flow). A comparison of curves of MHD flow with that of non-MHD flow shows that a growing magnetic parameter retards the velocity of the flow field at all points as a result of the magnetic pull of the Lorentz force acting on the flow field. Higher the parameter, the sharper is the reduction in the velocity of the flow field.

4.1.2 Effect of suction parameter (a)

Figure 2 shows the effect of suction parameter (a) on the velocity profiles of the flow field. As the suction parameter grows in the flow field, the velocity suffers a decrease in magnitude at all points. The reduction in the velocity at any point in the flow field is faster as the suction parameter becomes larger. The velocity profiles of our findings are in good agreement with those of Makinde *et al*. [18] and Das *et al*. [22]. One interesting result of our analysis is greater suction leads to a faster reduction in the velocity of the flow field and for a ≥ 2, a flow reversal occurs near the plate. Hence in order to restrict the flow reversal, the suction parameter should not be chosen beyond this limit.

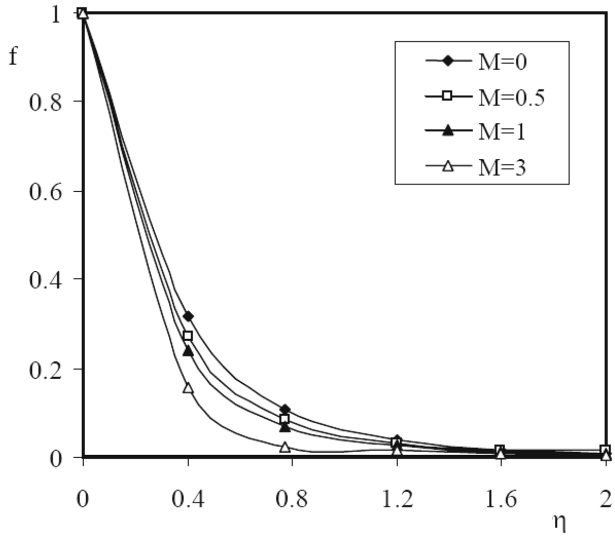

Figure 1. Velocity profiles against η for different values of M with $P_r = 0.71,\ S_c = 0.22,\ G_r = 1,$ $G_c = 1, a = 1,\ K_p = 1$

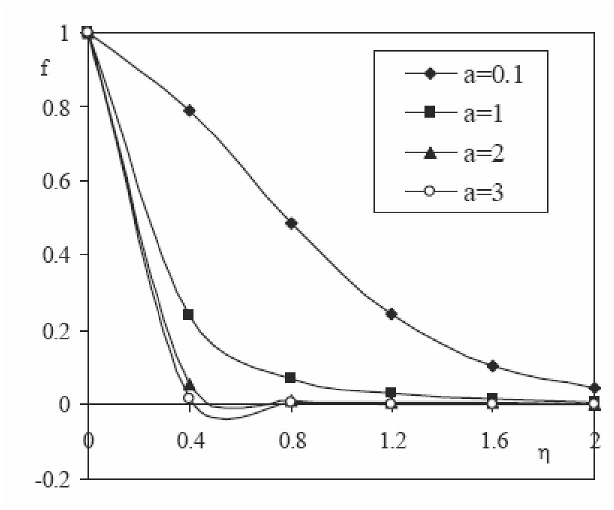

Figure 2. Velocity profiles against η for different values of a with $P_r = 0.71,\ S_c = 0.22,\ G_r = 1,$ $G_c = 1, M = 1,\ K_p = 1$

4.1.3 Effect of permeability parameter (K_p)

Figure 3 shows the velocity profiles against the non-dimensional distance η for different values of the permeability parameter (K_p) keeping other parameters of the flow field constant. The permeability parameter is found to accelerate the velocity of the flow field at all points. Higher the permeability parameter, the more prominent is the increase in velocity.

4.1.4 Effect of Grashof number for heat transfer (G_r)

The effect of Grashof number for heat transfer (G_r) on the velocity profiles of the flow field is presented in Figure 4. In this figure, the velocity of the flow field is plotted against η for different values of the Grashof number for heat transfer (for G_r>0 corresponding to cooling of the plate) keeping other parameters of the flow field constant. A study of the curves of the figure shows that the Grashof number for heat transfer (G_r) accelerates the velocity of the flow field at all points due to the action of convection current on the flow field. The effect of Grashof number for heat transfer (G_r) on the velocity of the flow field closely agrees with those of Makinde *et al*. [18] and Das *et al.* [22].

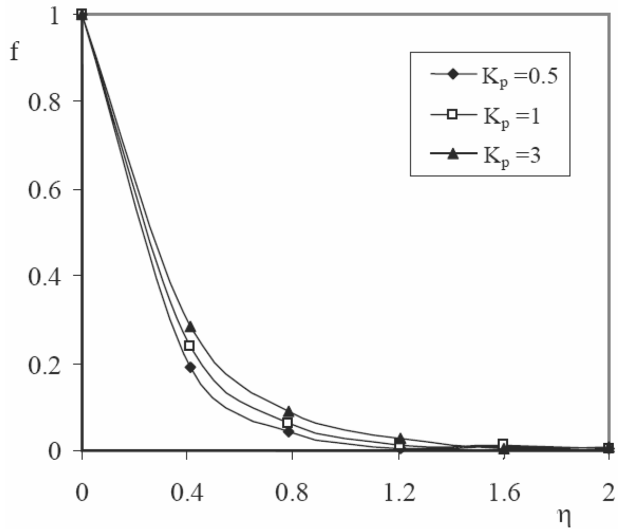

Figure 3. Velocity profiles against η for different values of K_p with $P_r = 0.71$, $S_c = 0.22$, $G_r = 1$, $G_c = 1$, $M = 1$, a=1

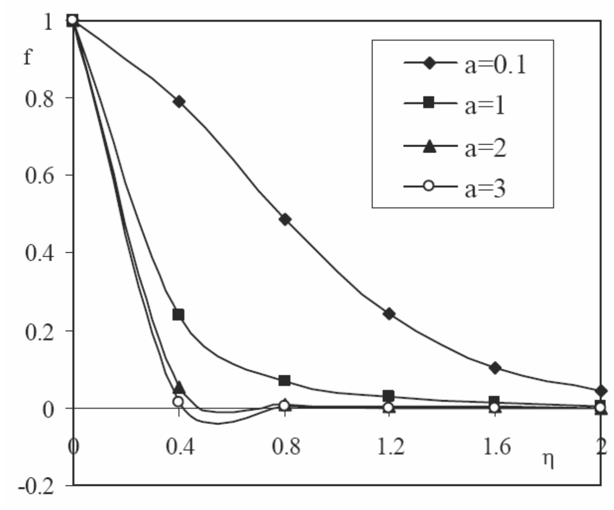

Figure 4. Velocity profiles against η for different values of G_r with $P_r = 0.71$, $S_c = 0.22$, $K_p = 1$, $G_c = 1$, $M = 1$, a=1

4.1.5 Effect of Grashof number for mass transfer (G_c)

The Grashof number for mass transfer (G_c) is a measure of mass transfer effect on the velocity field due to the diffusion of foreign mass in the flow field. Figure 5 depicts the effect of G_c on the velocity profiles of the flow field. Comparing the curves of the said figure, it is observed that a growing Grashof number for mass transfer has an accelerating effect on the velocity of the flow field at all points.

4.2 Temperature field

The temperature of the flow field is found to change with the variation of suction parameter (a) and Prandtl number (P_r) .These variations in the temperature profiles of the flow field are shown in Figures 6 and 7. The temperature profiles closely match with those of Makinde *et al*. [18] and Das and his associates [22].

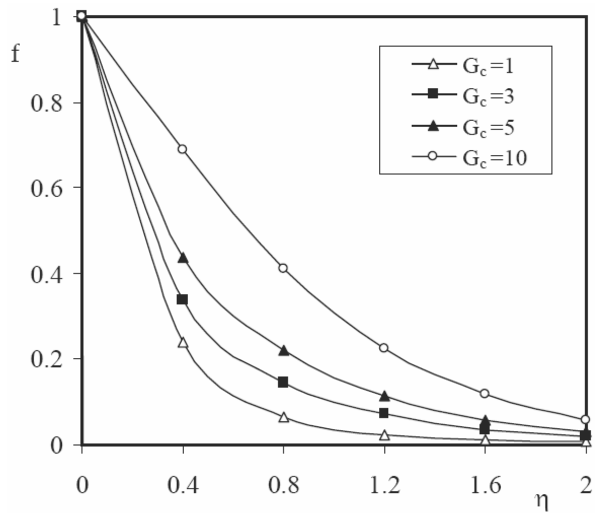

Figure 5. Velocity profiles against η for different values of G_c with $P_r = 0.71$, $S_c = 0.22$, $K_p = 1$, $G_r = 1$, $M = 1$, a=1

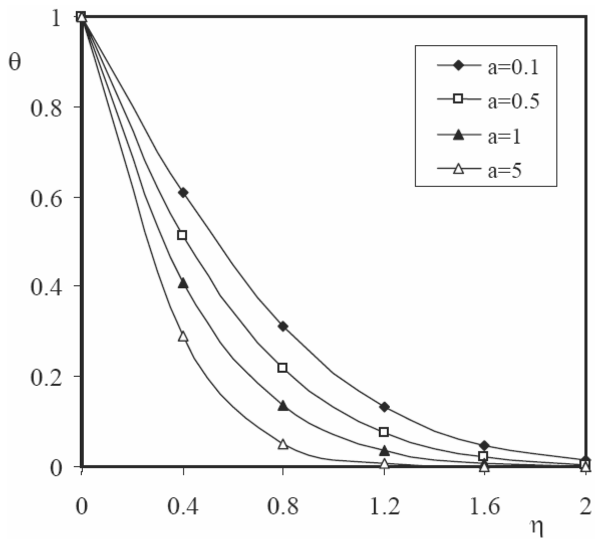

Figure 6. Temperature profiles against η for different values of a with $P_r = 0.71$

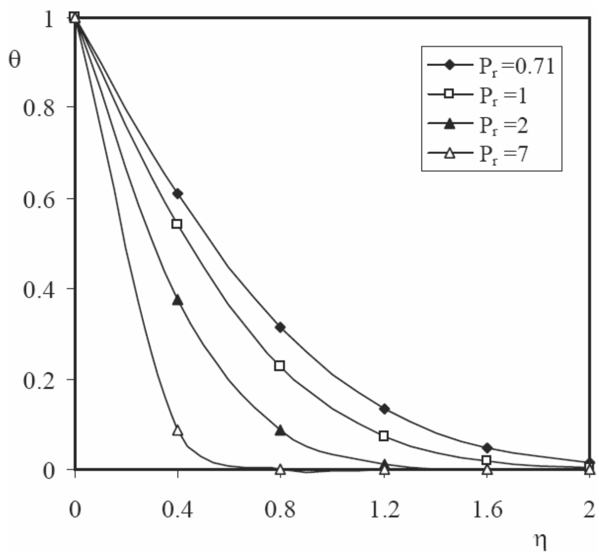

Figure 7. Temperature profiles against η for different values of P_r with a= 1

4.2.1 Effect of suction parameter (a)

Figure 6 depicts the temperature profiles against the non-dimensional distance η for various values of suction parameter (a) keeping Prandtl number (P_r) as constant. An increase in the suction parameter is found to diminish the temperature of the flow field at all points. In other words, cooling of the plate is faster as the suction parameter becomes larger. Thus it may be concluded that larger suction leads to faster cooling of the plate. Our result is in good agreement with those of Makinde *et al*. [18] and Das and his co-workers [22].

4.2.2 Effect of Prandtl number (Pr)

Figure 7 shows the plot of temperature of the flow field against the non-dimensional distance η for different values of Prandtl number (P_r) taking suction parameter (a) as constant. Comparing the curves of Figure 6, it is observed that the temperature of the flow field decreases in magnitude as P_r increases. Thus, a higher Prandtl number leads to faster cooling of the plate. Further, the temperature falls off more rapidly for water (P_r=7.0) in comparison to air (P_r=0.71). The effect of Prandtl number on temperature field closely agrees with those of Makinde *et al*. [18] and Das and his associates [22].

4.3 Concentration distribution

The concentration boundary layer thickness of the flow field is found to change more or less with the variation of suction parameter (a) and the Schmidt number (S_c). These variations are shown graphically in Figures 8 and 9 respectively.

4.3.1 Effect of suction parameter (a)

Figure 8 shows the variation in the concentration distribution of the flow field against the non-dimensional distance η in presence of H_2, a lighter diffusive species (S_c=0.22) for different values of the suction parameter. The suction parameter is found to decrease the concentration boundary layer of the flow field at all points. It is further observed that greater suction leads to a sharper reduction in the concentration boundary layer of the flow field.

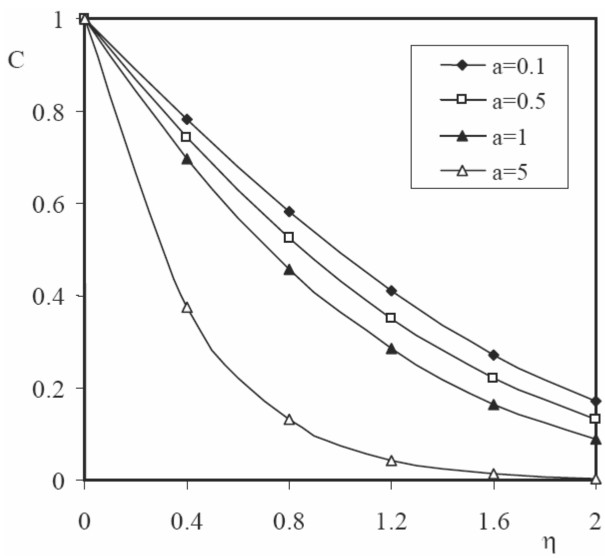

Figure 8. Concentration profiles against η for different values of a with $S_c = 0.22$

4.3.2 Effect of Schmidt number (S_c)

The variation in the concentration distribution of the flow field in presence of foreign species such as H_2, He, H_2O vapour and NH_3 in the flow field due to the variation in the Schmidt number is shown in Figure 9. Curves with S_c=0.22, 0.30, 0.60 and 0.78 respectively, represent the concentration distribution in presence of H_2, He, H_2O vapour and NH_3 in the flow field. The effect of growing Schmidt number is to decrease the concentration boundary layer of the flow field at all points. It is further found that the reduction in the concentration boundary layer of the flow field is more significant in presence of a higher diffusive species. Again, the concentration distribution of the flow field falls slowly and steadily for H_2

and He but falls very rapidly for NH_3 in comparison to H_2O vapour. Thus H_2O vapour can be used for maintaining normal concentration in the flow field while H_2 can be used for maintaining effective concentration in the flow field. One important feature of this finding is in order to reduce the concentration boundary layer of the flow field the presence of a higher diffusive species is essential.

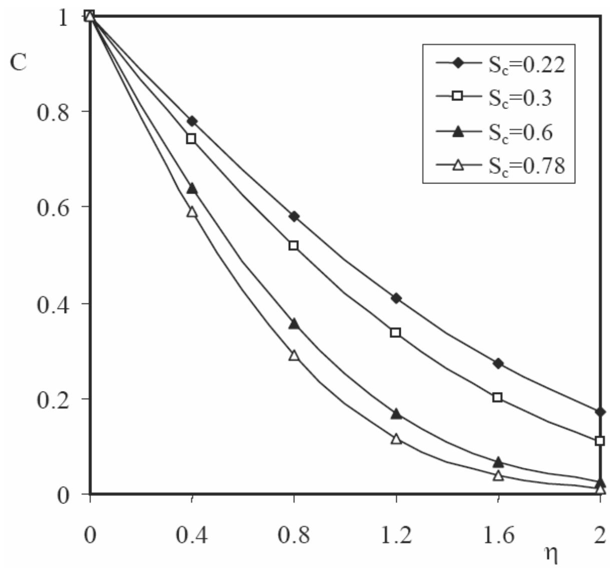

Figure 9. Concentration profiles against η for different values of S_c with a= 1

4.4 Heat flux and skin friction

The local heat flux at the plate in terms of Nusselt number (N_u) and the non-dimensional skin friction (τ') are entered in Table 1 for different values of suction parameter (a). A growing suction parameter is found to enhance the local heat flux and the skin friction at the wall. The results obtained for local heat flux and skin friction in our investigation closely agree with those of Makinde *et al.* [18] and Das *et al.* [22].

Table 1. Variation of heat flux (N_u) and skin friction (τ') with 'a' for P_r = 0.71, M=1, G_r=1, G_c=1, K_p=1

a	N_u	τ'
0.1	1.04299514	0.22061735
1.0	2.00275564	3.65187201
2.0	3.23732738	7.78556883

5. Conclusions

The above analysis brings out the following important features of physical interest on the velocity, temperature and the concentration distribution of the flow field.

1. A growing magnetic parameter (M) retards the velocity of the flow field at all points as a result of the magnetic pull of the Lorentz force acting on the flow field.
2. The reduction in velocity at any point in the flow field is faster as the suction parameter (a) becomes larger. Thus, greater suction leads to a faster reduction in the velocity of the flow field.
3. The effect of increasing the permeability of the medium (larger K_p) is to accelerate the velocity of the flow field at all points. Higher the permeability parameter, the more prominent is the increase in velocity.
4. As we increase the Grashof numbers for heat and mass transfer (G_r, G_c), the velocity of the flow field enhances at all points.
5. At any point in the flow field, the cooling of the plate is faster as the suction parameter (a) and Prandtl number (P_r) become larger. Thus greater suction/Prandtl number leads to faster cooling of the plate.

6. The effect of growing Schmidt number (S_c) and the suction parameter (a) is to decrease the concentration boundary layer of the flow field at all points. A more diffusive species has a significant decrease in the concentration boundary layer thickness of the flow field.
7. A growing suction parameter enhances both skin friction (τ') and the local heat flux (N_u) at the wall.

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