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Buoyancy Effects on Free Convective MHD Flow in the Presence of Heat Source/Sink

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Abstract

A mathematical model is analyzed in order to study the role of buoyant forces on magnetohydrodynamic (MHD) flow of an electrically conducting fluid over a stretching sheet embedded in a porous medium subject to transverse magnetic field. The effects of mass buoyancy, uniform heat source/sink and first order chemical reaction have been taken into account in the present study. The governing boundary layer equations are transformed into ordinary differential equations by a similarity transformation. The transformed equations are then solved numerically by using shooting technique with the help of Runge-Kutta fourth order method. The effect of various parameters on velocity, temperature and concentration profiles is depicted in graphs and discussed. The inclusion of magnetic field is counterproductive in diminishing the velocity distribution whereas reverse effect is encountered in case of temperature and concentration profiles. The concentration of the fluid decreases insignificantly with the increase in Biot number. The work of previous authors is compared with the present as particular cases.

Keywords

Heat source/sink; stretching sheet; Mass transfer; Runge-Kutta method.

1. Introduction

The study of heat and mass transfer in non-Newtonian fluids due to a permeable stretching surface is of great importance. The flow over a stretching surface has crucial applications in many engineering processes. Studies on boundary layer flows of viscous fluids due to a uniformly stretching sheet have been carried out by many authors due to several applications in different fields of Science and Technology in recent past. For instance, Nazar *et al.* [1], Kumari *et al.* [2], Hayat *et al.* [3], and many others have worked in this area of interest.

Heat transfer over a stretching surface has many engineering applications in industry. The flow of fluids through porous media in a rotating system is of interest for instance to the petroleum engineering movement of oil and gas through the reservoir; and to the hydrologist who is interested in the study of migration of underground water. Study of flows through porous media in a rotating system also finds applications in geothermal energy systems, oil and gas recovery, and in the spread of pollutants in groundwater. Research on flows through porous media has lately been applied in the manufacture of industrial machinery and computer disk drives, Herrero *et al.* [4]. In the field of energy conservation, attention has been focused on the use of saturated porous materials for insulation in storage tanks so as to control the rate of heat transfer. Insulating underground water pipes prevents the water in the pipes from freezing during winter. Acharya et al.[5] studied free convective fluctuating hydromagnetic flow through porous media past a vertical porous plate with variable temperature and heat source.

The stretching problems for steady flow have been used in various industrial manufacturing processes, such as non-Newtonian fluid flow through porous medium. Flow over a stretching sheet on the boundary layer was initiated by Sakiadis [6,7]. Futher, the work on two dimensional flow over a stretching sheet problem was extended by Crane [8]. Gupta and Gupta [9] have studied the heat and mass transfer over a stretching sheet with suction and blowing, Carragher and Crane [10], Mishra et al.[11], and Mohanty et al.[12] investigated the flow past a stretching surface considering different aspects of the problem and Dutta *et al.* [13] studied flow over a stretching sheet with uniform heat flux. Problem of flow and heat transfer through a porous medium over a stretching surface are considered by Cortell [14], Chauhan and Agrawal [15], Chauhan and Rastogi [16]. Abel *et al.* [17] studied the effect of heat transfer of a second grade fluid past over a stretching sheet in the presence of non-uniform heat source or sink. Further, Xu [18] studied the heat transfer effect in an electrically conducting fluid over a stretching surface in the presence of uniform free stream.

When temperature difference exists between the solid-fluid interface and the fluid in the free stream, a thermal boundary layer is formed. The fluid particles in contact with the solid-fluid interface acquire the temperature of the interface. If the temperature of the interface is higher than that of the ambient fluid, the kinetic energy of the molecules of the adjacent fluid particles increases. These particles in turn exchange the acquired kinetic energy with those fluid particles in the adjacent fluid layers further away from the interface. This process continues in the adjacent fluid layers and temperature gradients develop in the fluid. Based on the aforesaid properties, the effects of variable viscosity on a convective fluid along a vertical surface through a porous medium were analyzed by Lai and Kulacki [19]. Further, Kafoussian and Williams[20] investigated the effects of temperature-dependent viscosity on convective boundary layer flow past a vertical isothermal flat plate. Pantokratoras [21] made a theoretical study to investigate the effect of variable vidcosity.

Concentration is a measure of how much of a given species is dissolved in another substance per unit volume. Concentration boundary layer manifests itself when species concentration difference exists between the solid- fluid interface and the free stream region of the fluid. The region in which the species concentration gradient exists is known as the concentration boundary layer. The species transfer takes place through the process of diffusion and convection, and is governed by the properties of the concentration boundary layer.

An exact similarity solution in a closed analytical form under various physical conditions of the steady boundary layer flow of an incompressible viscous fluid over a linearly stretching plate has been investigated by many researchers [22,23]. Bhukta *et al.* [24] studied heat and mass transfer on magnetohydrodynamic flow of a viscoelastic fluid through porous media over a shrinking sheet and Cortell [25-26], analyzed the flows over a non-linear stretching sheet. Baag et al.[27] investigated the hydromagnetic flow of a viscoelastic fluid through porous medium between infinite parallel plates with time dependent suction. The flow geometries and the superimposed similarity solutions of the governing boundary layer equations in a non-linear stretching sheet have been given by Ferdows et al. [28]. Mahapatra *et al.* [29] investigated heat transfer due to magnetohydrodynamic stagnation-point flow of a power-law fluid towards a stretching surface in presence of thermal radiation and suction/injection. Further, Baag et al.[30] have studied entropy generation analysis for viscoelastic MHD flow over a stretching sheet embedded in a porous medium. Dessie and Kishan [31] have studied the MHD effects on heat transfer over stretching sheet embedded in porous medium with variable viscosity, viscous dissipation and heat source/sink.

In the rate of cooling, where water is widely used as the cooling additives, porous medium also plays a vital role. Cooling rate depends on the physical properties of the cooling medium but the practical situation demands for physical properties with variable characteristics. Best of our knowledge one such properties is thermal conductivity, which is assumed to vary linearly with temperature. Eldabe and Mohamed [32] have examined and obtained the solution for both heat and mass transfer of a non-Newtonian electrically conducting MHD fluid in the presence of heat source over an accelerating surface through a porous medium. Researchers [33-35] have studied the variable thermal conductivity effect in the presence of temperature dependent heat source/sink.

In the present study we have considered mass transfer along with heat transfer on MHD mixed convective unsteady flow of an electrically conducting fluid over a stretching sheet embedded in a porous medium. In many industrial applications thermal diffusion is associated with mass diffusion if there is a difference in concentration of diffusive species. Many authors including Saville and Churchil [36,37] may be considered as the origin of the modern research on the effect of mass transfer on free convection flow. Further, Gebhart and Pera[38] studied the laminar flows which arise in the flow due to the concentration of the gravity force and density differences caused by simultaneous difference of thermal energy and chemical species neglecting the thermal diffusion and diffusion-thermo (Soret and Dufour) because the level of species concentration is very low. Mishra et al.[39] studied the free convective flow of viscoelastic fluid in a vertical channel with Dufour effect. To maintain the temperature of the convective fluid porous media is very widely used to insulate a heated body. They are considered to be useful in diminishing the natural free convection which would otherwise occur intensely on the heated surface.

Now, regarding the inclusion of Darcy dissipation which has not been considered as Pal and Mondal [40]. Gebhart [41] has studied that the viscous dissipation in a convective flow is important when the flow domain is at extremely low temperature of of extreme size or in high gravity field. In such situation when we consider the flow through porous medium the Darcy dissipation term cannot be neglected in the energy equation because it is of the same order of magnitude with viscous dissipation term.

Recently, Rashidi et al.[42] employed a method to examine free convective heat and mass transfer in a steady incompressible two-dimensional hydromagnetic fluid flow over a stretching surface in a porous medium. In his discussion he has restricted to free convection by taking thermal Grashof number in the absence of heat source and chemical reaction. So, in the present paper is intended to carryover our discussion by incorporating solutal Grashof number in the presence of uniform heat source and first order chemical reaction. For the validation of the present work, we have compared our result with the earlier published work by withdrawing the aforesaid physical parameters through graphs. The numerical computation of skin friction, rate of heat and mass transfer are also compared and discussion is made for variation of different pertinent physical parameters through tables.

Table 1. Values of $f''(0)$ for suction parameter f_w=-0.75 (injection) when $Bi \to \infty$

M	Kp	λ_t	λ_c	Cortell [25]	Ferdows et al.[28]	Rashidi et al. [42]	Present
0	0	0	0	0.453521	0.453523	0.4535499	0.4535857
1	0	0	0	--	--	--	0.972898
1	0.5	0	0	--	--	--	1.162977
1	0.5	0.5	0	--	--	--	0.958674
1	0.5	0.5	0.5	--	--	--	0.7106817

Table 2. Values of $f''(0)$ for suction / injection parameter f_w=0 when $Bi \to \infty$

M	Kp	λ_t	λ_c	Cortell [25]	Ferdows et al.[28]	Rashidi et al. [42]	Present
0	0	0	0	0.677647	0.6776563	0.6776563	0.677624
1	0	0	0	--	--	--	1.2036865
1	0.5	0	0	--	--	--	1.3956002
1	0.5	0.5	0	--	--	--	1.198806
1	0.5	0.5	0.5	--	--	--	0.913743

Table 3. Values of $f''(0)$ for suction parameter f_w=0.75 when $Bi \to \infty$

M	Kp	λ_t	λ_c	Cortell [25]	Ferdows et al.[28]	Rashidi et al. [42]	Present
0	0	0	0	0.984417	0.984439	0.9844401	0.9844083
1	0	0	0	--	--	--	1.484789
1	0.5	0	0	--	--	--	1.6719962
1	0.5	0.5	0	--	--	--	1.4981102
1	0.5	0.5	0.5	--	--	--	1.1709172

Table 4. Values of $-\theta'(0)$ for different parameters when $Bi \to \infty$

M	Kp	$-\theta'(0)$	Pr	S	$-\theta'(0)$	Nr	Bi	$-\theta'(0)$
0	0	0.8218768	0.71	0	0.489503	0	0	0
1	0	0.707061	1	0	0.591525	0.5	3	0.626455
1	0.5	0.6681824	1	0.5	0.333367	4/3	3	0.465881
			1	-0.5	0.741035	4/3	10	0.5372263

Table 5. Values of $-\phi'(0)$ for different parameters when $Bi \to \infty$

Sc	Kc	$-\phi'(0)$	Sc	Kc	$-\phi'(0)$
0.22	-4	1.057724	0.78	0	0.900079
0.22	0	0.42137		-4	2.027572
	4	-8.57773		4	1.478293

2. Flow analysis

The steady, two-dimensional, viscous incompressible electrically conducting fluid over a stretching sheet embedded in a saturated non-Darcian porous medium on the plane y=0 of a coordinate system shown in flow geometry (Fig.1). Two equal and opposite forces are applied along $x-$axis so that the surface is stretched keeping the origin fixed. The stretching velocity is assumed to be $u=cx^{1/3}$, c is any constant. The magnetic Reynolds number of the conducting fluid is assumed to be very small so that Hall effect and induced magnetic field may be neglected. Therefore, magnetic field effect in momentum is taken into account in the present study.

Moreover, the flow domain is subject to non-uniform transverse magnetic field $B(x)=B_0x^{-1/3}$ is applied normal to the sheet (Fig.1). Studies of magnetohydrodynamics boundary layer flow over flat plates and in the saturated region of bodies with transverse magnetic field demonstrate that the magnetic field reduces skin friction and heat transfer and increase the sock detachments distances. Following Rashidi et al. [42] the governing boundary equations of momentum, energy and concentration for free convection under Boussinesq's approximation are

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0. \tag{1}$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\mu\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}\right)-\sigma B^2(x)u-\frac{\mu}{kp(x)}u+\rho g\beta_T\left(T-T_\infty\right)+\rho g\beta_c(\mathrm{C}-\mathrm{C}_\infty) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\kappa}{\rho C_P}\frac{\partial^2 T}{\partial y^2}+\frac{16\sigma^* T_\infty^3}{\rho C_P k_1}\left(\frac{\partial^2 T}{\partial y^2}\right)+\frac{Q}{\rho C_P}(T-T_\infty) \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}-K_c^*(\mathrm{C}-\mathrm{C}_\infty) \tag{4}$$

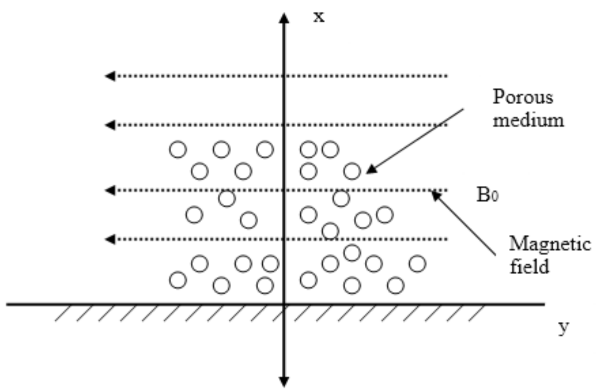

Fig.1. Schematic Diagram

The corresponding boundary conditions are

$$\left.\begin{array}{llll} u=U_w(x)=cx, & v=v_w, -\kappa\dfrac{\partial T}{\partial y}=h_f(x)(T_w-T), & C=C_w=C_\infty+bx, & at\ \ y=0 \\ u=0, & T\to T_\infty, & C\to C_\infty, & as\ y\to\infty \end{array}\right\} \tag{5}$$

To solve the governing boundary layer equations (1)-(4), the following stream function and similarity transformations are introduced ([42]):

$$\psi(x,y) = x^{2/3}c^{1/2}\upsilon^{1/2} f(\eta), \qquad \eta = ycx^{-1/3}\upsilon^{-1/2} \quad . \tag{6}$$

and $\quad T_w(x,y) = T_\infty + ax, \theta(\eta) = \dfrac{T - T_\infty}{T_w - T_\infty}, C_w(x,y) = C_\infty + bx, \phi(\eta) = \dfrac{C - C_w}{C_w - C_\infty}$. (7)

where a and b are constant with $a, b \geq 0$.

The flow is caused by the stretching of the sheet which moves in its own plane with the surface velocity $U_w(x) = cx$ where c, the stretching rate.

Substituting the above mentioned stream function and similarity variables (6) and (7) into the governing boundary layer equations (2)–(4) we obtain a system of non-linear ordinary differential equations with appropriate boundary conditions as follows:

$$f''' + \frac{2}{3} ff'' - \frac{1}{3} f'^2 - (Mn + Kp) f' + \lambda_t\theta + \lambda_c\phi = 0 \tag{8}$$

$$\frac{1}{\Pr}(1 + Nr)\theta'' + \frac{1}{3}(2 f\theta' - 3 f'\theta) + S\theta = 0 \tag{9}$$

$$\frac{1}{Sc}\phi'' + \frac{1}{3}(2 f\phi' - 3 f'\phi) - Kc\phi = 0 \tag{10}$$

$$\left.\begin{aligned} &f(\eta) = f_w, f'(\eta) = 1, \theta'(\eta) = -Bi[1 - \theta(\eta)], \phi(\eta) = 1, \quad && at \;\; \eta = 0 \\ &f'(\eta) = 0, \theta(\eta) = 0, \phi(\eta) = 0 && as \;\; \eta \to \infty \end{aligned}\right\} \tag{11}$$

$$\left.\begin{aligned} &K_p = \frac{v}{ckp}, M^2 = \frac{\sigma B_0^2}{c\rho}, \lambda_t = \frac{g\beta_T(T_w - T_\infty)}{c^2} x^{1/3}, \lambda_c = \frac{g\beta_c(C_w - C_\infty)}{c^2} x^{1/3}, \\ &\Pr = \upsilon/\alpha, Kc = \frac{Kc^*}{c}, \Pr_\infty = \frac{\rho_\infty v_\infty C_p}{\kappa}, Sc = \frac{v}{D_m}, Nr = \frac{16\sigma^* T_\infty^3}{3kk_1} \end{aligned}\right\}$$

where $f_w = \dfrac{3x^{1/3}v_w}{2\upsilon^{1/2}c^{1/2}}$ and $Bi = \dfrac{3\upsilon^{1/2}x^{1/3}h_f}{kc^{1/2}}$.

The physical quantities of interest are skin friction C_f , Nusselt number Nu_x and Sherwood number Sh_x, which are defined as

$$C_f = \frac{\tau}{\rho U_w^2/2}, Nu_x = \frac{xq_w}{k(T_w - T_\infty)}, Sh_x = \frac{xq_m}{D_m(C_w - C_\infty)} \tag{12}$$

where surface shear stress, surface heat and mass flux are defined as

$$\tau = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, \; q_w = -\kappa\left(\frac{\partial T}{\partial y}\right)_{y=0}, \; q_m = -D_m\left(\frac{\partial C}{\partial y}\right)_{y=0}. \tag{13}$$

Using the non-dimensional variables (6), Eqs. (12) and (13) are as follows

$$\frac{C_f}{\mathrm{Re}_x^{1/2}} = f''(0), \frac{Nu_x}{\mathrm{Re}_x^{1/2}} = -\theta'(0), \frac{Sh_x}{\mathrm{Re}_x^{1/2}} = -\phi'(0), \tag{14}$$

where $\mathrm{Re}_x = \dfrac{xU_w(x)}{\upsilon}$.

In the case when $M = Kp = \lambda_t = \lambda_c = f_w = 0$, the governing momentum equation (8) and the boundary conditions reduced to

$$f'''(\eta) + \frac{2}{3} f(\eta) f''(\eta) - \frac{1}{3}(f'(\eta))^2 = 0 \tag{15}$$

$$f(0) = 0, f'(0) = 1 \text{ and } f'(\eta) \to 0 \text{ } as \text{ } \eta \to \infty. \tag{16}$$

The exact solution of (16) and (17) is (see [25])

$$f(\eta) = 1 - e^{-\eta} \tag{17}$$

However, the governing Eqs. (8)-(10) are solved numerically since these equations and associated boundary condition have no exact solution.

3. Results and discussion

The robust Runge-Kutta method followed by shooting technique has been used to solved the couples non-linear Eqs. (8) - (10) subject to boundary conditions Eq. (11) in the present discussion. The numerical solutions are obtained to exhibit the effects of emerging physical parameters on the velocity, temperature and concentration distributions through Figs.2-11.

In the present study free convective steady flow of an electrically conducting fluid over a stretching sheet embedded in a porous medium subject to transverse magnetic field in the presence of uniform heat source/sink has been investigated. Main objective of the following discussion is to bring out the effects of additional parameters introduced such as buoyancy mass buoyancy (λ_t), porous matrix (Kp), heat source (S) and chemical reaction (Kc) parameters besides the other parameters appear in the free convective diffusion problem. The case of Rashidi et al.[42] can be retrieved when $\lambda_c = Kp = S = Kc = 0$.

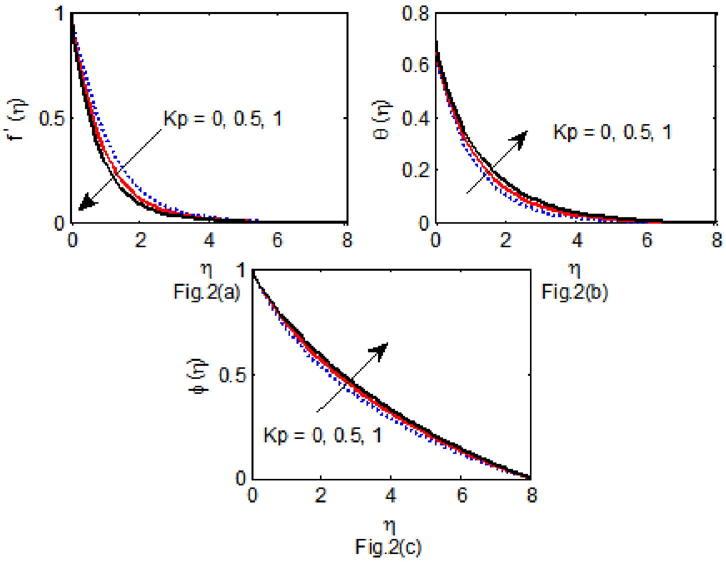

Fig.2. Comparison plot for Bi=2.0, f_w=0.1, λ_c=0, S=0, Kc=0, Nr=0

Fig.2 shows the comparison plot for velocity, temperature and concentration in the absence of above said parameters. From Figs. 2(a), (b) and (c) it is clear that in the absence of porous matrix and mass Grashof number the present result is in good agreement with the result of Rashidi et al. [42]. Also presence of porous matrix retards the velocity profile significantly (Fig.2(a)) where as reverse effect is encountered in the temperature and concentration profiles (Figs.2(b),(c)) i.e. both the temperature and concentration profiles gets enhanced in the presence of porous matrix.

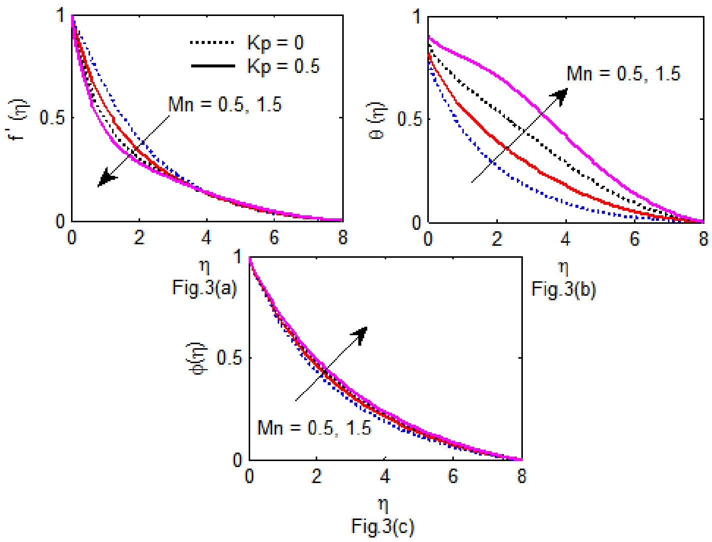

Fig.3. Effect of Mn for Bi=2, f_w=0.1, λ_t=λ_c=Nr=Kc=0.5, Sc=0.22

Fig.3 exhibits the effect of magnetic parameter on velocity, temperature and concentration profiles in both the absence and presence of porous medium. The Lorentz force is a resistive force which resists the fluid motion significantly. Therefore, the velocity profile decreases with the increase in the magnetic parameter (Fig.3(a)). On the other hand, high value of magnetic parameter ($Mn = 1.5$) the temperature becomes maximum throughout in the thermal boundary layer and it rises significantly with the increasing value of magnetic parameter (Fig.3(b)). From Fig.3(c) it is clear that the concentration profile also increases with the increase in magnetic parameter in the both absence and presence of porous matrix but its effect is insignificant. The profile is asymptotic in nature.

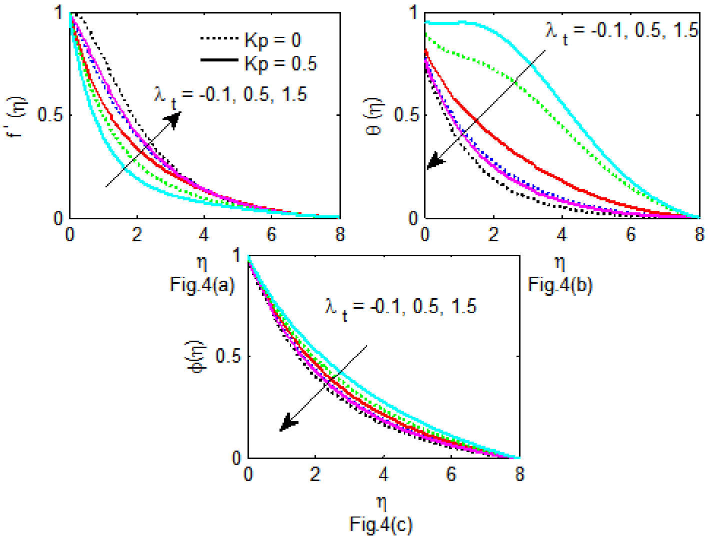

Fig.4. Effect of λ_t for f_w=0.1, Mn=λ_c=Nr=S=Kc=0.5, Sc=0.22

Fig.4 displays the variation of thermal buoyancy parameter on velocity, temperature and concentration profiles in the absence / presence of porous matrix. The negative value of $\lambda_t(\lambda_t = -0.5)$ represents heating of the sheet and positive value of $\lambda_t(\lambda_t = 1)$ represents the cooling of the sheet. From Fig.4(a) it is observed that incase of heating the velocity profile decreases and it becomes minimum near the wall of the sheet and further decreases to meet the boundary condition. It is also interesting to note that cooling enhance the velocity profile significantly. The hike in temperature is remarked in case of heating in the thermal boundary layer. The hike is due to overriding effect of the difference of the plate temperature and ambient state temperature i.e. $T_w - T_\infty$ and further it decreases in case of cooling for both presence / absence of porous matrix (Fig.4(b)). The concentration level also decreases from heating to cooling (Fig.4(c)).

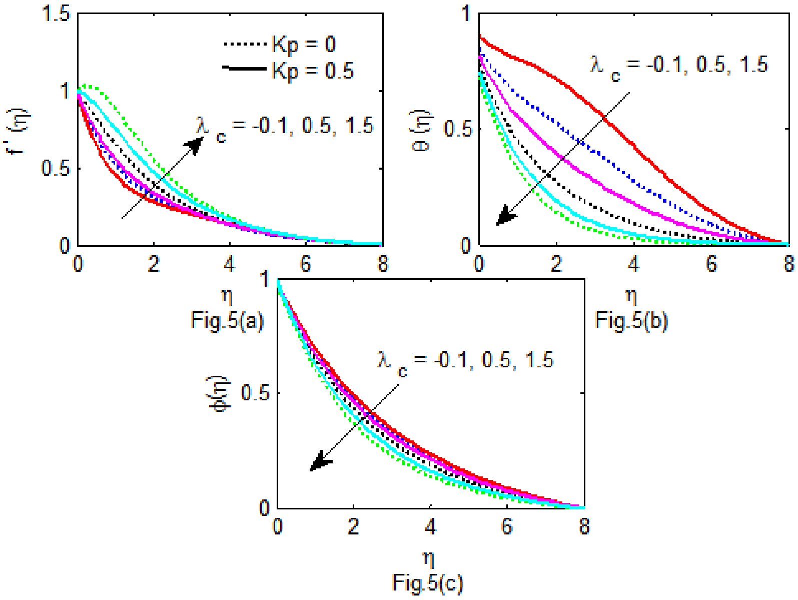

Fig.5. Effect of λ_c for f_w=0.1, Mn=λ_t=Nr=S=Kc=0.5, Sc=0.22

The effect of mass buoyancy parameter is well exhibited in Fig. 5 on velocity, temperature and concentration profiles for both absence / presence of porous matrix. The similar observation is shown in the profiles as described in Fig.4 for thermal buoyancy parameter.

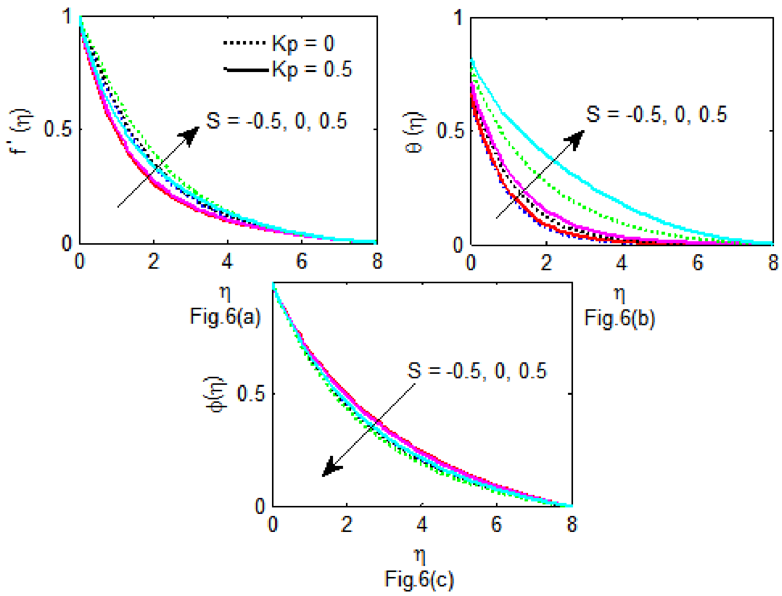

Fig.6. Effect of S for f_w=0.1, Mn=λ_t=λ_c=Nr=Kc=0.5, Sc=0.22

Fig.6 exhibits the heat source / sink parameter effect on flow, heat and mass transfer profiles in both the absence / presence of porous matrix. It is to note from Fig.6(a) and (b) that both the velocity and temperature profiles are increases with the increase in heat source parameter whereas sink reduces both the profiles. Further, from Fig.6(c) it is observed that source decreases the concentration profile and sink enhance it irrespective of the absence / presence of porous matrix.

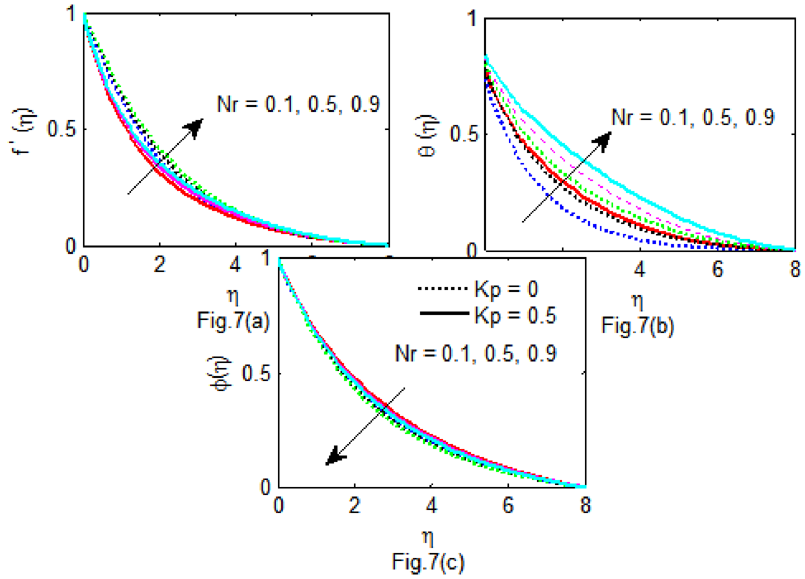

Fig.7. Effect of Nr for f_w=0.1, Nr=Mn=λ_t=λ_c=Kc=0.5, Sc=0.22

Fig.7 shows the effect of radiation on the velocity, temperature and concentration profiles for both the absence / presence of porous matrix. From Figs. 7(a) and (b) it is observed that there is a hike in both the velocity and temperature profiles due to increase in radiation parameter where as the concentration profile reduces. This is due to the fact that inclusion of magnetic parameter. Suction also plays an important role on velocity distribution.

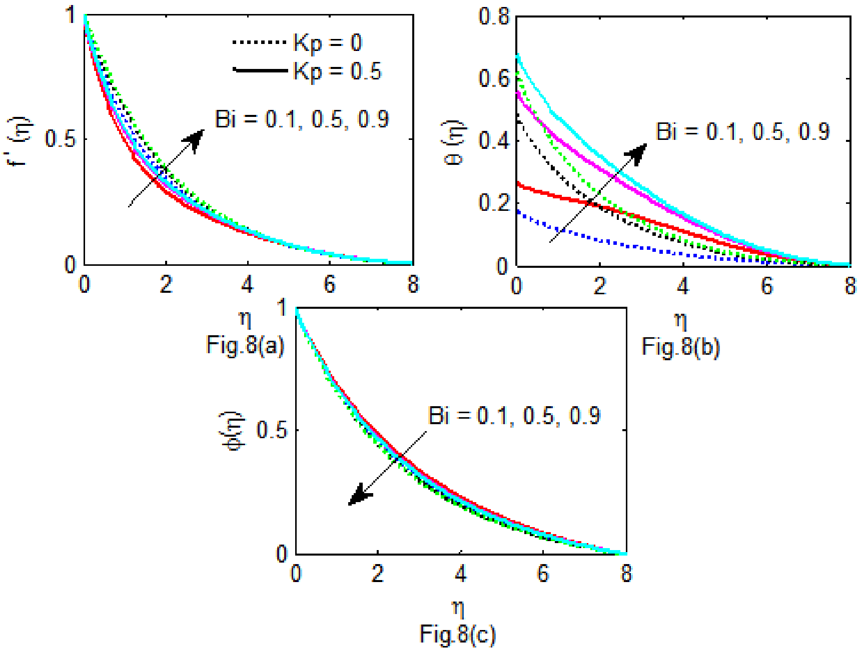

Fig.8. Effect of Bi for f_w=0.1, Mn=λ_t=λ_c=Nr=Kc=0.5, Sc=0.22

The effect of Bi on the velocity, temperature and concentration profiles is well exhibited in Fig.8 in both the absence / presence of porous matrix. It is clear to remark that the velocity and temperature distributions enhance due to increase in Biot number Figs. 8(a) and (b). As Biot number increases the plate resistance also increases henceforth, the velocity increases throughout the boundary layer. The profile is asymptotic in nature. Also thermal resistance of the fluid decreases and convective heat transfer on the right side of the plate increases which causes a rise in temperature. Further, from Fig.8(c) it is clear to note that the concentration profile has a retarding effect on the concentration boundary layer. As a result the concentration of the fluid decreases insignificantly with the increase in Biot number.

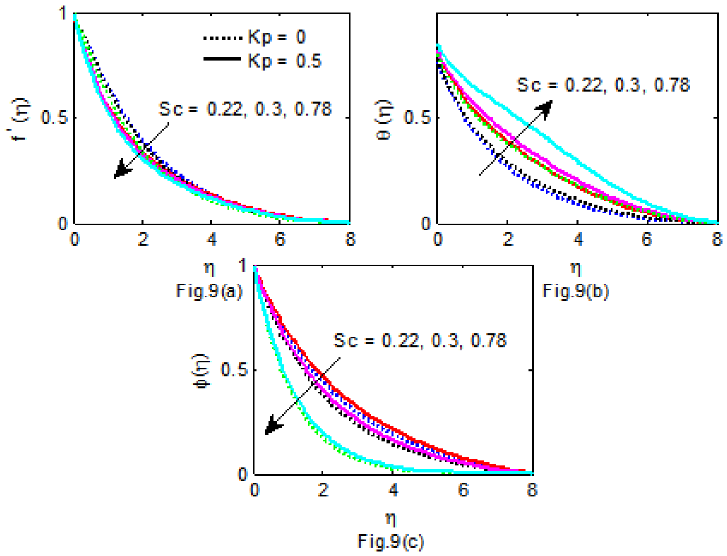

Fig.9. Effect of Sc for f_w=0.1, Mn=λ_t, λ_c=Nr=Kc=0.5, Bi=2

Fig.9 illustrates the effect of Schmidt number on the velocity, temperature and concentration profiles. Fig. 9(a) shows that the velocity profile decreases with the increase in Schmidt number near the plate but it is became insignificant after that. The temperature profile increases significantly with the increase in Sc in both the absence / presence of porous matrix as shown in Fig. 9(b). The effect of heavier species is on concentration profile is remarked significantly in Fig. 9(c). It is observed that heavier species diminishes the concentration level throughout the concentration boundary layer. Hence it is concluded that heavier species is counterproductive to lower down the concentration of the fluid at all the point in its boundary layer for both the absence / presence of porous matrix.

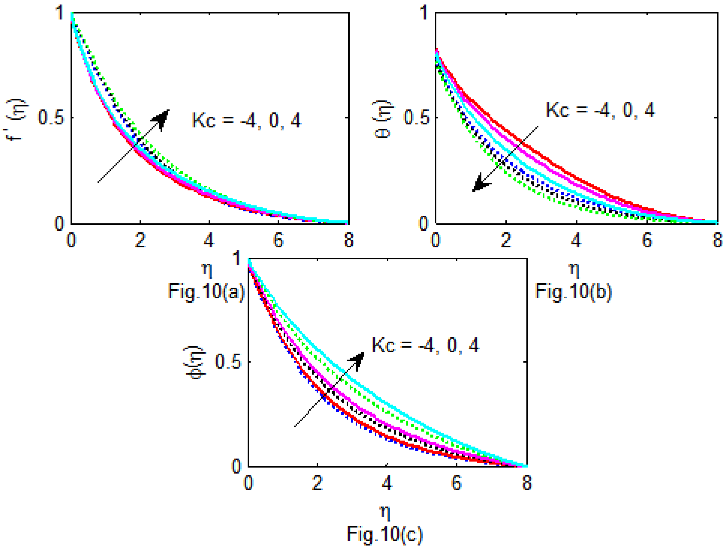

Fig.10. Effect of Kc for f_w=0.1, Mn=λ_t=λ_c=Nr=S=0.5, Sc=0.22

Fig.10 shows the effect of chemical parameter (Kc) on velocity, temperature and concentration profiles for both the absence / presence of porous matrix. In the present discussion $Kc > 0$ and $Kc < 0$ represent the destructive and constructive chemical reaction respectively. Also $Kc = 0$ i.e. no chemical reaction case is discussed in the present study. From Fig.10(a) and (b) it is seen that velocity profile retards with the significant increase in chemical reaction parameter where as temperature profile enhances. It is interesting to note that the solutal concentration increases in the presence of destructive reaction ($Kc > 0$) but decreases in the presence of constructive reaction ($Kc < 0$) irrespective of the absence / presence of porous matrix.

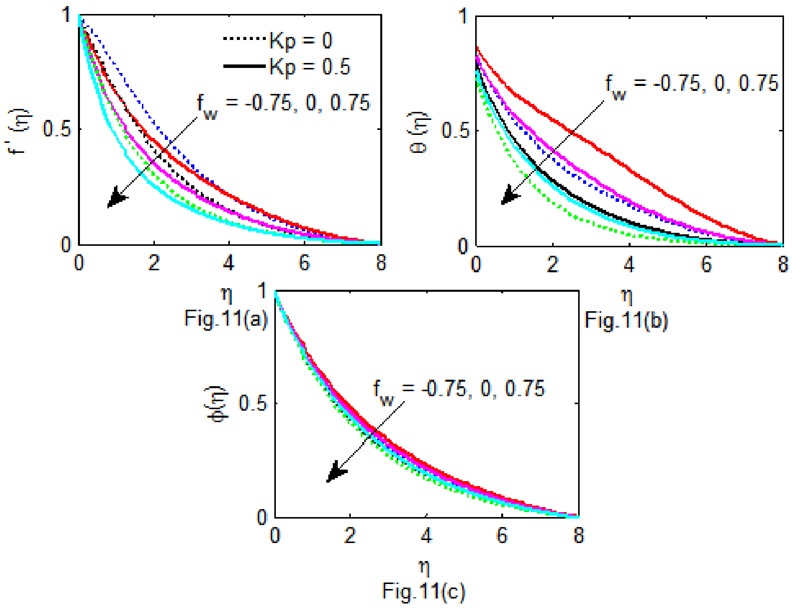

Fig.10. Effect of f_w for Mn=λ_t=λ_c=Nr=Kc=0.5, Sc=0.22, Bi=2

Fig.11 exhibits the physical significance of the suction / injection on velocity, temperature and concentration profile. Both the suction (f_w>0)/ injection (f_w<0) are compared with the impermeable case (f_w=0). It is observed that suction retards all the profiles in both the absence/presence of porous matrix significantly. Whereas reverse effect is encountered in case of injection.

4. Conclusions

- The solutal buoyancy effect and electric field overrides the fluctuations in inertia and viscous forces to enhance the velocity field.
- Thinning of boundary layer is affected by heavier diffusing species.
- Thinning of thermal boundary layer occurs under the influence of higher wall concentration, higher variable viscosity and space dependent heat source parameters.
- Heavier species as well as induced electric field opposes the fluid motion and enhance the temperature uniformly in the flow domain.
- The combined effect of solutal convection current as well as destructive chemical reaction gives rise to mass absorption.
- Chemical reaction plays a vital role for the structure of solutal/thermal boundary layer.
- The destructive chemical reaction and upstream solutal convective current is favorable for the growth of solutal boundary layer.

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Nomenclature

a, b	constants	B	transverse magnetic field
B_0	magnetic field strength	Bi	Biot number
C	concentration of species	c	stretching rate
C_p	specific heat at constant temperature	C_f	skin friction coefficient
C_w	concentration at wall	C_∞	ambient concentration
D_m	mass diffusion	f	nondimensional velocity
f_w	suction parameter	g	acceleration due to gravity
h_f	film thickness	kp	porous medium
Kc	chemical reaction parameter	Kp	porous parameter
k_1	mean absorption coefficient	Mn	magnetic parameter
Nu_x	local Nusselt number	Nr	radiation parameter
Pr	Prandtl number	Pr_∞	ambient Prandtl number
Q	non-uniform heat source / sink	q_m	surface mass flux
q_w	surface heat flux	Re_x	local Reynolds number
S	heat source/sink parameter	Sc	Schmidt number
Sr	Soret number	Sh_x	local Sherwood number
T	fluid temperature	T_w	stretching sheet temperature
T_∞	ambient temperature	u	velocity of the fluid in x-direction
v	velocity of the fluid in y-direction	(x, y)	flow directional coordinate

Greeck symbol

η	similarity variable	κ	thermal conductivity
β_T	coefficient of thermal expansion	β_C	coefficient of mass expansion
θ	non-dimensional temperature	θ_r	variable viscosity constant
ρ	density of the fluid	σ	magnetic permeability
λ_t	thermal buoyancy parameter	λ_c	mass buoyancy parameter
μ	fluid viscosity	υ	kinematic viscosity
α	thermal diffusivity	σ^*	Stephan-Boltzman constant
τ	surface shear stress		