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Mass Transfer on MHD Flow of a Casson Fluid Through a Porous Media Due to a Stretching Sheet With the Effect of Chemical Reaction and Suction

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***Abstract**: In this paper we investigated mass transfer effects on MHD flow of a Casson fluid through a porous media due to a stretching surface with chemical reaction and suction. We used a similarity transformation to obtain a system of non-linear ordinary differential equations, which was then solved analytically using Optimal Homotopy Asymptotic method (OHAM). Analytical results are obtained for the skin friction coefficient and the local Sherwood numbers and as well as for the velocity field and concentration profile for selected values of the governing parameters, such as the Hartman number M, the suction S, the porous medium parameter K, the Schmidt number Sc and the chemical reaction parameter γ. It was shown that the velocity field decreases and the concentration profile increases when the Hartman number M increases. The influence of the suction parameter is to reduce both the velocity field and the concentration profile. We obtained that there is a good agreement between the present result and those in the literature.*

***Keywords**: Casson fluid; MHD; Suction; Mass transfer; chemical reaction; OHAM.*

1. INTRODUCTION

Mass transfer is the net movement of mass from one location, usually meaning stream, phase, fraction or component, to another. Mass transfer occurs in many processes, such as absorption, evaporation, drying, precipitation, membrane filtration, and distillation. Mass transfer is used by different scientific disciplines for different processes and mechanisms. The phrase is commonly used in engineering for physical processes that involve diffusive and convective transport of chemical species within physical systems. Some common examples of mass transfer processes are the evaporation of water from a pond to the atmosphere, the purification of blood in the kidneys and liver, and the distillation of alcohol. In industrial processes, mass transfer operations include separation of chemical components in distillation columns, absorbers such as scrubbers or stripping, absorbers such as activated carbon beds, and liquid-liquid extraction. Mass transfer is often coupled to additional transport process, for instance in industrial cooling towers. These towers couple heat transfer to mass transfer by allowing hot water to flow in contact with air. The water is cooled by expelling some of its content in the form of water vapor.

Ramana Reddy [1] analyzed the effects of magneto-hydrodynamic force and buoyancy on convective heat and mass transfer flow past a moving vertical porous plate in the presence of thermal radiation and chemical reaction. The effects of viscous dissipation and mass transfer on unsteady MHD oscillatory flow of a viscous fluid between two vertical plates with porous medium and non-uniform wall temperature were investigated by Kiran Kumari and Mamta Goyal [2]. Manjula Jonnadula et al.[3] studied the flow, heat and mass transfer characteristics of an electrically conducting, incompressible and viscous fluid past a stretching porous medium. Magnetohydrodynamic (MHD) boundary flow of a nanofluid over an exponentially stretching sheet were studied by Ferdows et al.[4]. Magneto hydrodynamics (MHD; also magneto-fluid dynamics or hydro-magnetics) is the study of the magnetic properties of electrically conducting fluids. Examples of such magneto-fluids include plasmas, liquid metals, salt water and electrolytes.

Farhad Ali et al. [5] analyzed the influence of thermal radiation on some unsteady magnetohydrodynamic (MHD) free convection flows of an incompressible Brinkman type fluid past a vertical flat plate embedded in a porous medium with the Newtonian heating boundary condition. They obtained that temperature and velocity increase on increasing radiation and Newtonian heating parameters. However, the magnetic and porosity parameters are found to be quite opposite. The boundary layer flow of a second grade fluid over a permeable stretching surface with arbitrary velocity and appropriate wall transpiration were investigated by Ahmad and Asghar [6]. A mathematical model of the steady boundary layer flow of nanofluid due to an exponentially permeable stretching sheet with external field is presented by Bhattacharyya and Layek [7]. They have shown that the magnetic field makes enhancement in temperature and nanoparticle volume fraction, where as the wall mass transfer through the porous sheet causes reduction of both. For the brownian motion, the temperature increases and the nanoparticle volume fraction decreases. Heat transfer rate becomes low with increase of Lewis number. For the thermophoresis effect, the thermal boundary layer thickness becomes larger. a mathematical model for a two-dimensional, steady, incompressible electrically conducting, laminar free convection boundary layer flow of a continuously moving vertical porous plate in a chemically reactive medium in the presence of a magnetic field were presented by Ibrahim and Makinde [8]. Visalakshi and Vasanthabhavam [9] studied an exact solution of unsteady flow past a parabolic starting motion of the infinite vertical plate with constant heat flux, in the presence of uniform mass diffusion. Gurram et al.[10] considered MHD Casson fluid of viscous, incompressible, electrically -conducting fluid past an inclined moving plate in the presence of a uniform transverse magnetic field, thermal and concentration buoyancy effects.

Zakaria [11] analyzed the heat transfer from a non-isothermal stretching sheet in the presence of a transverse magnetic field. The axis-symmetric boundary layer flow and heat transfer past a permeable shrinking cylinder subject to surface mass transfer were studied by Bhattacharya [12]. It is found that the velocity in the boundary layer region decreases with the curvature parameter and increases with suction mass transfer. Moreover, with the increase of the curvature parameter, the suction parameter and Prandtl number, the heat transfer is enhanced. The problem of free convective flow of a viscous incompressible fluid through a porous medium bounded by an infinite vertical porous plate in the presence of transverse magnetic field were considered by Anus Jhankal [13].

The following authors also briefly studied about mass transfer in the presence of chemical reaction (Kandasamy et al, [14]; Hayat et al., [15]; Ziabaksh et al., [16]; Makinde, [17]; Ibrahim and Makinde, [18]; Bhattacharyya and Layek, [19]; Hayat et al., [20]; Makinde, [21]). Shehazad et al. [22] studied the effect of mass transfer in the magneto-hydrodynamic flow of a Casson fluid over a porous stretching sheet in the presence of a chemical reaction. However, mass transfer on MHD flow of Casson fluid through a porous media due to a stretching sheet with chemical reaction and suction is not studied adequately in a comprehensive way. Thus to the best of authors knowledge, so far the simultaneous effects of these quantities in the presence of chemical reaction and suction through a porous medium has not been analyzed. Hence, this problem is investigated. The governing boundary layer equations are reduced to a system of non-linear ODEs using similarity transformation and the results are solved analytically using Optimal Homotopy Asymptotic Method (OHAM). A parametric study is conducted to illustrate the influence of various governing parameters on the velocity field, concentration profile, skin friction coefficient and Sherwood number are investigated in detail.

2. MATHEMATICAL FORMULATION

Let us consider a steady two dimensional flow of magneto hydrodynamic (MHD) and incompressible flow of a Casson fluid over a stretching surface at $y=0$ through a porous media shown by figure I. In the Cartesian coordinate system we considered that the $x-axis$ is taken to be parallel to the surface and the $y-axis$ is perpendicular to the surface. The region of the half space $y>0$ is occupied by the fluid. Also the phenomenon of the mass transfer with chemical reaction is retained. The fluid flow we considered is subjected to a constant magnetic field strength B_0 is located in the $y-$direction. It is considered that the magnetic Reynolds number is very small so that the induced magnetic field is negligible in comparison to the applied magnetic field and the flow is taken to be steady. The fluid properties are constant.

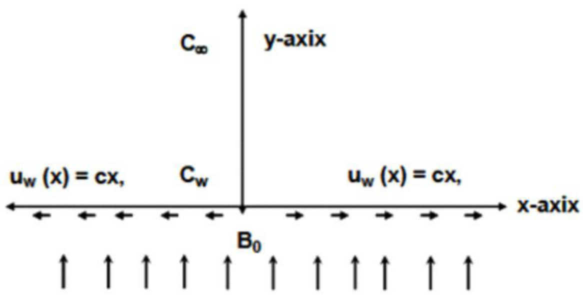

Fig. 1: Physical sketch of the present problem

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + \frac{p_y}{\sqrt{2\pi}}\right) e_{ij}, \pi > \pi_c \\ 2\left(\mu_B + \frac{p_y}{\sqrt{2\pi}}\right) e_{ij}, \pi < \pi_c \end{cases} \quad (1)$$

Here μ is the dynamic viscosity, μ_B the plastic dynamic viscosity of Casson fluid, p_y is the stress of Casson fluid, $\pi = e_{ij}e_{ji}$ is the $(i,j)^{th}$ component of the deformation rate Casson fluid (π is the product of the component of deformation rate with itself), π_c is a critical value of this product based on the non-Newtonian model. The equations governing the steady boundary layer flow of the Casson fluid are given by (Mustafa et al., 2012).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (2)$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\left(+\frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u - \frac{\nu}{K^*}u \quad (3)$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - k_1 C \quad (4)$$

The corresponding boundary conditions associated to the differential equations are:

$$u = u_w(x) = cx, v = -v_0, C = C_w \; at \; y = 0, \quad (5)$$

$$u \to 0, \quad C \to C_\infty \; as \; y \to \infty \quad (6)$$

where $u \; and \; v$ represent the velocity components in the $x-$ and $y-$directions, $\beta = \mu_B\sqrt{\frac{2\pi_c}{p_y}}$ the non-Newtonian Casson parameter, $\mathbf{\nu} = \frac{\mu_B}{\rho}$ the kinematic viscosity, D the mass diffusion, C the concentration field and k_1 the reaction rate, ρ –the fluid density, σ –the electrical conductivity of the fluid, C –the species concentration in the boundary layer, C_∞ –the species concentration in fluid far away from the plate, B_0 –the magnetic induction by introducing the following similarity transformation we can made equations (2) to (6) dimensionless.

$$\left.\begin{array}{c} u = cxf'(\eta), \; v = -\sqrt{cvf(\eta)} \\ \eta = y\sqrt{\frac{c}{\nu}}, \; \varphi = \frac{C-C_\infty}{C_w-C_\infty}, \end{array}\right\} \quad (7)$$

hence, using equations (3,4,5,6,7) the governing boundary layer equation is transformed in to couples of ODEs:

$$\left(1+\frac{1}{\beta}\right)f''' + ff'' - f'^2 - Mf' - Kf' = 0, \quad (8)$$

$$\varphi'' + Scf\varphi' - Sc\gamma\varphi = 0, \quad (9)$$

The corresponding boundary conditions become

$$f = S, f' = 1, \varphi = 1 \; at \; \eta = 0, \quad (10)$$

$$f' = 0, \varphi = 0 \; as \; \eta \to \infty, \quad (11)$$

where Eq. (2) is satisfied identically, $M = \sigma B_0{}^2/\rho c$ the Hartman number, $Sc = \nu/D$ the Schmidt number, $\gamma = k_1/c$ the chemical reaction parameter , $K = \nu/K^*c$ the porous medium parameter and $S = v_0/\sqrt{\nu c}$ the suction parameter.

The skin friction coefficient and the local Sherwood number can be written as:

$$C_f = \frac{\tau_w}{\rho u^2{}_w}, \; Sh = \frac{xj_w}{D(C_w - C_\infty)}, \quad (12)$$

where τ_w is the skin friction (or shear stress along the stretching surface) and j_w is the mass flux from the surface, defined by the following relations:

$$\tau_w = \langle \mu_B + \frac{p_y}{\sqrt{2\pi_c}} \rangle \left[\frac{\partial u}{\partial y}\right]_{y=0}, \quad j_w = -D\left[\frac{\partial C}{\partial y}\right]_{y=0} \quad (13)$$

Now Eqs. (12) and (13) gives:

$$\left.\begin{array}{c} Re_x{}^{1/2} = -\left(1+\frac{1}{\beta}\right)f''(0) \\ \frac{Sh}{Re_x^{\frac{1}{2}}} = -\varphi'(0) \end{array}\right\} \quad (14)$$

3. SOLUTION BY OHAM

Basic Principles of OHAM: The following are some basic principles of OHAM as developed in [38-39] in the following five steps.

Let us consider the following differential equation

$$A[V(x)]+a(x)=0, x\in\Omega \tag{15}$$

Where Ω is problem domain, $A(v)=L(v)+N(v)$ where L, N are linear and nonlinear operator of $V(x)$, $a(x)$ is known function. Construct an optimal Homotopy equation as

$$(1-p)\left[L(\phi(x;p))+a(x)\right]-H(p)\left[A(\phi(x;p))+a(x)\right]=0 \tag{16}$$

Where $0\le p\le 1$ is an embedding parameter, $H(p)=\sum_{k=1}^{m}p^k C_k$ is auxiliary function on which the convergence of the solution greatly dependent. The auxiliary function $H(p)$ also adjust the convergence domain and control the convergence region.

Expand $\phi(x;p,C_j)$ in Taylor's series about p ,one has an approximate solution:

$$\phi(x;p,C_j)=v_0(x)+\sum_{k=1}^{k}v_k(x,C_j)p^k,\ j=1,2,3... \tag{17}$$

Many researchers have observed that the convergence of the series Eq (17) depends upon $C_j\,(j=1,2,....,m)$,if it is convergent then, we obtain:

$$\tilde{V}=V_0(x)+\sum_{k=1}^{m}V_k(x;C_j) \tag{18}$$

Substituting Eq.(18) in Eq.(15),we obtain the following residual:

$$R(x;C_j)=L(\tilde{v}(x;C_j))+a(x)+N(\tilde{v}(x;C_j)) \tag{19}$$

If $R(x;C_j)=0$, then $\tilde{v}$ will be the exact solution. For nonlinear problems, generally this will not be the case. For determining $C_j,(j=1,2,...,m)$, Galerkin's Method, Ritz Method or the method of least squares can be used.

Solution of Eq (8) -(9) with corresponding boundary conditions (10) to (11) can be solved using Optimal Homotopy asymptotic method as:

using the above steps we can write Eqs. 8 and 9 respectively as

$$\left.\begin{array}{c}(1-p)(f''+f')-\\ H_1(p)\left[\left(\left(1+\frac{1}{\beta}\right)f'''+ff''-f'^2-(M+K)f'\right)\right)-\\ (f''+f')]=0\\ (1-p)(\varphi'+\varphi)-\\ H_2(p)[(\varphi''+Scf\varphi'-Sc\gamma\varphi)-(\varphi'+\varphi)]=0\end{array}\right\} \tag{20}$$

Obviously when $p=0$ and $p=1$ we get from (17)

$$\phi(\eta,0)=v_0,\ \text{and}\ \ \phi(\eta,1)=v(\eta) \tag{21}$$

Thus as p increases from 0 to 1, the solution varies from $v_0(\eta)$ to $v_1(\eta)$. for $p=0$ we can write

$$L(v_0(\eta))+g(\eta)=0, B(v_0)=0, \tag{22}$$

The auxiliary equation $H(p)$ is chosen as

$$H(p)=pC_1+p^2C_2+p^3C_3+\cdots, \tag{23}$$

Where C_1, C_2, C_3 ...are constants.

in the same way we can write the auxiliary equations for the momentum, and mass transfer equations of (20) as:

$$\left.\begin{array}{l}f=f_0+pf_1+p^2f_2+\cdots\\ \varphi=\varphi_0+p\varphi_1+p^2\varphi_2+\cdots\\ H_1(p)=pC_{11}+p^2C_{12}+\cdots\\ H_2(p)=pC_{21}+p^2C_{22}+\cdots\end{array}\right\} \tag{24}$$

Expanding $\phi(\eta,p)$ in series with respect to p one can write:

$$\phi(\eta,p,C)_i=v_0(\eta)+\sum_{k\ge 1}v_k(\eta,C_i)p^k, i=1,2,3\ ... \tag{25}$$

Now following the method and substituting(24) in to (20) we can write:

The Zeroth order as:

$$\left.\begin{aligned} p^0: \quad & f_0'' + f_0' = 0 \\ f_0(0) = \mathrm{S}, f_0'(0) &= 1, f_0(\infty) = 0 \\ \varphi_0' + \varphi_0 &= 0 \\ \varphi_0(0) = 1, \varphi_0(\infty) &= 0 \end{aligned}\right\} \quad (26)$$

The first order:

$$\left.\begin{gathered} p^1: -\mathrm{f0}' + \mathrm{c11f0}' + \mathrm{c11f0}'^2 - \mathrm{f0}'' + \mathrm{c11f0}'' \\ -\mathrm{c11f0f0}'' - \left(1+\tfrac{1}{\beta}\right)\mathrm{c11f0}''' \\ +\mathrm{f1}' + \mathrm{f1}'' + \mathrm{c11f0}'(M+K) = 0 \\ f_1'(0) = 0, f_1(0) = 0, f_1(\infty) = 0 \\ -\varphi 0 + \mathrm{c21}\varphi 0 - \varphi 0' + \mathrm{c21}\varphi 0' - \mathrm{c21}\varphi 0'' \\ +\varphi 1 + \varphi 1' - \mathrm{c21f0}\varphi 0'\mathrm{Sc} \\ +\mathrm{c21}\varphi 0\gamma\mathrm{Sc} = 0 \\ \varphi_1(0) = 0, \varphi_1(\infty) = 0 \end{gathered}\right\} \quad (27)$$

The second order:

$$\left.\begin{gathered} p^2: \mathrm{c12f0}' + \mathrm{c12f0}'^2 + \mathrm{c12f0}'' - \\ \mathrm{c12f0f0}'' - \left(1+\tfrac{1}{\beta}\right)\mathrm{c12f0}''' - \mathrm{c11f0}''\mathrm{f1} \\ -\mathrm{f1}' + \mathrm{c11f1}' + 2\mathrm{c11f0}'\mathrm{f1}' \\ -\mathrm{f1}'' + \mathrm{c11f1}'' - \mathrm{c11f0f1}'' \\ -\left(1+\tfrac{1}{\beta}\right)\mathrm{c11f1}''' + \mathrm{f2}' + \mathrm{f2}'' + \mathrm{c12f0}'(M+K) \\ +\mathrm{c11f1}'(M+K) = 0 \\ f_2'(0) = 0, f_2(0) = 0, f_2(\infty) = 0 \\ \mathrm{c22}\varphi 0 + \mathrm{c22}\varphi 0' - \mathrm{c22}\varphi 0'' - \\ \varphi 1 + \mathrm{c21}\varphi 1 - \varphi 1 + \mathrm{c21}\varphi 1 - \mathrm{c21}\varphi 1'' + \varphi 2 + \\ \varphi 2' - \mathrm{c22f0}\varphi 0'\mathrm{Sc} - \mathrm{c21f1}\varphi 0'\mathrm{Sc} - \mathrm{c21f0}\varphi 1\mathrm{Sc} \\ +\mathrm{c22}\varphi 0\gamma\mathrm{Sc} + \mathrm{c21}\varphi 1\gamma\mathrm{Sc} = 0 \\ \varphi_2(0) = 0, \varphi_2(\infty) = 0 \end{gathered}\right\} \quad (28)$$

Hence, we get general solution of Eq. (18) as

$$\begin{cases} f_0(\eta) = e^{-x}(-1 + e^x + e^x S) \\ \varphi_0(\eta) = e^{-\eta} \end{cases} \quad (29)$$

$$\begin{cases} f_1 = \mathrm{c11}e^{-x}(-1 + (1+\frac{1}{\beta}) - \\ M - K - S)(-1 + e^x - x) \\ \varphi_1 = -\mathrm{c21}e^{-2x}(\mathrm{Sc} - e^x\mathrm{Sc} - \\ e^x x + e^x\mathrm{Sc}x + e^x\gamma\mathrm{Sc}x + e^x S\mathrm{Sc}x) \end{cases} \quad (30)$$

For brevity, the solutions for $f_2(\eta)$, and $\varphi_2(\eta)$ are not presented here.

Hence, solutions for the momentum equation, heat transfer equation and mass transfer equations(up to second-order terms) are given by

$$\left.\begin{aligned} f(\eta) &= f_0(\eta) + f_1(\eta) + f_2(\eta) + \cdots \\ \varphi(\eta) &= \varphi_0(\eta) + \varphi_1(\eta) + \varphi_2(\eta) + \cdots \end{aligned}\right\} \quad (31)$$

by substituting the values of $f(\eta)$, and $\varphi(\eta)$ from (31) in to equations 8 and 9 we can find residuals as

$R_1(\eta, C_{11}, C_{12})$, and $R_2(\eta, C_{21}, C_{22})$, subsequently we can obtain the Jacobians J_1, and J_2 as

$$J_1(\eta, C_{11}, C_{12}) = \int_0^b R_1^{\,2}(\eta, C_{11}, C_{12})d\eta \quad (32)$$

$$J_2(\eta, C_{21}, C_{22}) = \int_0^b R_2^{\,2}(\eta, C_{21}, C_{22})d\eta \quad (33)$$

With these known constants, approximate solution of the problem(to order m) can be determined very easily.

4. RESULTS AND DISCUSSIONS

Analytical results were obtained for the effects of chemical reaction and Suction on MHD flow of Casson fluid and mass transfer on a porous stretching sheet. Where analytical solution in terms of confluent hypergeometric series is possible only when the Soret effect is absent. The non- linear ordinary differential equations (8)-(9) subject to the given boundary conditions (10)-(11) were solved analytically using Optimal Homotopy Asymptotic Method (OHAM). To validate the accuracy of the analytical results, comparisons were made with previously published journals by Saleem ans El-Aziz (2008) and Andersson et al. (1994). as shown in Table 2, the results are in a good agreement.

The Skin friction coefficient - $(1+1/\beta)f''(0)$ and the local Sherwood number **-**$\varphi'(0)$ for different values of the chemical reaction parameter γ and when $\beta\to\infty$ and M = S=K = 0, Sc=1 are shown in Table 1.

The influence of the suction parameter on the velocity field and concentration field is illustrated in Fig. 2-3. We observed that both the velocity field and the concentration field decreases with an increase of the suction parameter. This is because Suction is an agent which causes resistance to the fluid flow. Fig.

4-5 illustrates the influence of the Hartman number on the velocity field and concentration field. Here, we observed that as the Hartman number increases the velocity field increases where as the concentration field increases. This is due to the fact that the applied magnetic field normal to the flow direction induces the drag in terms of a Lorentz force which provides resistance to flow. But in the case of the concentration field , both the concentration profiles and boundary layer thickness increases with an increase of the Hartman number. This shows that, the Hartman number decreases the resistive force.

Fig. 6-7 illustrates the influence of the porous parameter on the concentration field and velocity field. From the figure we observed that as the size of the porous parameter increases the velocity field decreases where as the concentration field increases. This is because the presence of a porous medium increases the resistance to the flow causing a decrease in the fluid velocity. Fig. 8-9 illustrates the influence of the Casson parameter on the velocity field and concentration field. From the figure we observed that the velocity field decreases but the concentration field increases when the Cassson parameter β increases. This is due to the fact that an increase in β leads to an increase in plastic dynamic viscosity that creates resistance in the flow of fluid and a decrease in fluid velocity is seen. But the concentration field and associated boundary layer thickness increases.

Fig. 10 shows the influence of the Schmidt number Sc on the concentration field. We observed that both the concentration field and the boundary layer thickness a decreasing function of the Schmidt number . from the physical point of view, the Schmidt number is dependent on the mass diffusion D and an increase in Schmidt number corresponds to a decrease in mass diffusion and the concentration profile is reduced. Fig.11 illustrates the effect of the chemical reaction parameter on the concentration profile. We observed that the concentration profile is a decreasing function of the chemical reaction parameter. Fig.12 illustrates the influence of the Casson parameter β vs K the porous medium parameter on ${Re_x}^{1/2} C_f$. This figure confirms that the skin friction coefficient increases with an increase of the porous medium parameter K and decreases with an increase of the Casson parameter β.

Fig.13 shows the influence of the Casson parameter β Vs K the porous medium parameter on the skin friction coefficient. Here we observed that the skin friction coefficient function is an increasing function of K but decreases with an increase of β. Fig 14. Illustrates the influence of the K Vs γ on the Sherwood number $Sh / {Re_x}^{1/2}$. Here we have seen that the Sherwood number is an increasing function of both K and γ. Fig.15 illustrates the influence of β Vs γ on the Sherwood number. The figure confirms that the Sherwood number is an increasing function of both.

5. CONCLUSIONS

This paper presents Mass transfer effects on MHD flow of Casson fluid through a porous media due to a stretching sheet in the presence of chemical reaction and suction. The Governing nonlinear partial differential equations were transformed in to ordinary differential equations using the similarity relation and solved analytically using the Optimal Homotopy Asymptotic Method (OHAM) . Based on the results described by the graph and table we can conclude that.

1. Both the velocity field and the concentration profile decreases with an increase of the suction parameter S.
2. The velocity profile decreases with an increasing of the Hartman number M, the porous medium parameter K and the Casson parameter β.
3. The concentration profile increases with an increase of the porous medium parameter K and the Casson parameter β but decreases with an increase of the Schmidt number and the chemical reaction parameter γ.
4. The skin friction coefficient increases with an increase of the porous medium parameter, but decreases with an increase of the Casson parameter β.
5. The Sherwood number increases with an increase of the porous medium parameter K, the Casson parameter β and the chemical reaction parameter γ.

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Tables and Figures

Table 1. Analytical values of the Skin friction coefficient - (1+1 / β)f ″(0) and the local Sherwood number -**φ′**(0) for different values of **β,** M, S,K, Sc and **γ**..

β	M	S	K	Sc	γ	$-(1+\frac{1}{\beta})f''(0)$	$-\varphi'(0)$
0.5	0.5	0.5	0.5	0.6	0.3	2.71231	0.808414
1						2.26545	0.799133
1.5						2.09215	0.793237
2						1.99881	0.789396
	0.0					1.77034	0.796872
	0.5					1.99881	0.789396
	1					2.20012	0.782692
	1.5					2.38102	0.776684
		0.6				2.43632	0.820839
		1				2.6662	0.982414
		1.5				2.9678	1.21442
			0.0			2.80275	1.22197
			0.6			2.99854	1.21302
			1.2			3.16858	1.00139
			2			3.36131	1.00044
				0.4		3.36131	0.890459
				0.8		3.36131	1.17303
				1.2		3.36131	1.25469
				2		3.36131	1.30779
					0.0	3.36131	0.960312
					0.4	3.36131	0.967742
					0.8	3.36131	1.30024
					1	3.36131	1.41528

Table 2: Comparison of values of $-\varphi'(0)$ for different values of γ when $\beta \to \infty$ and M = S=K = 0.0.

γ	Sc	Saleem ans El-Aziz (2008)	Andersson et al. (1994)	$-\varphi'(0)$
0.01	1	0.592	0.59157	0.593683
0.1	1	0.669	0.66902	0.664282
1	1	1.177	1.17649	1.17523
10	1	3.232	3.23122	3.23094

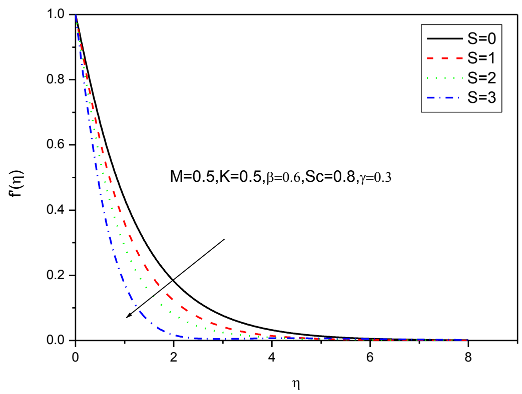

Fig 2. The influence of S on the velocity field

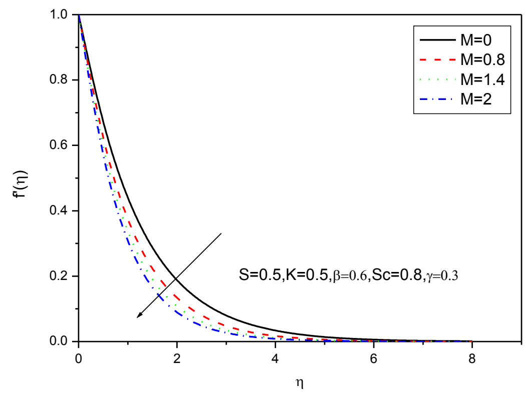

Fig 4. The influence of M on the velocity field

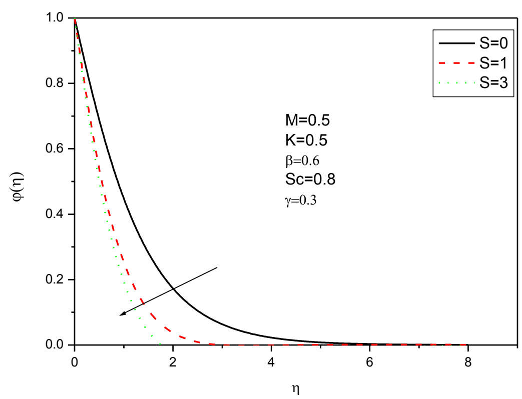

Fig 3. The influence of S on the concentration profile

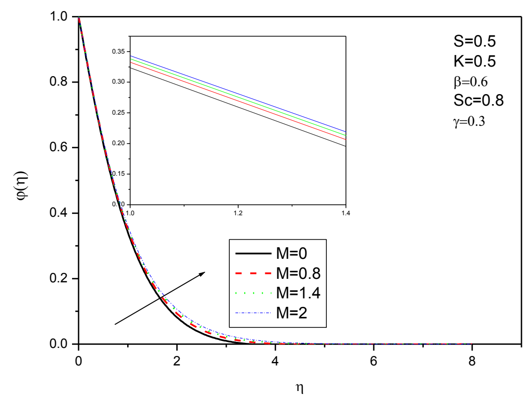

Fig 5. The influence of M on the concentration profile

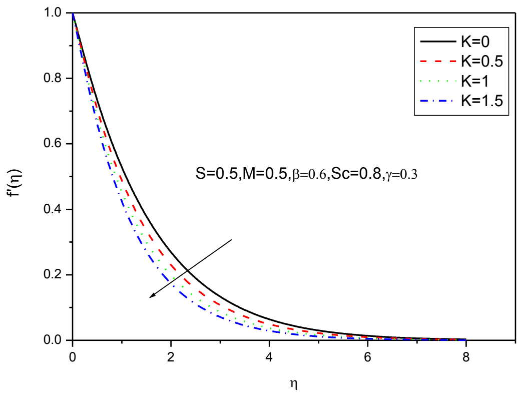

Fig 6. The influence of K on the velocity field

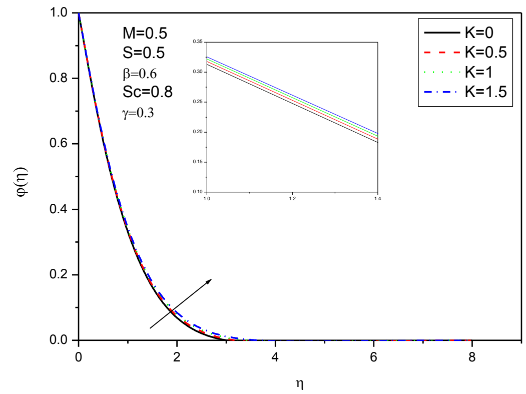

Fig 7. The influence of K on the concentration profile

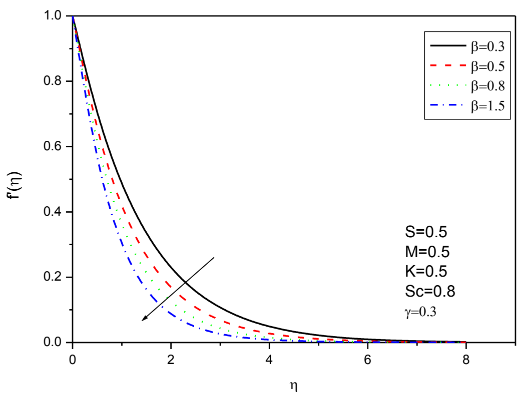

Fig 8. The influence of β on the velocity field

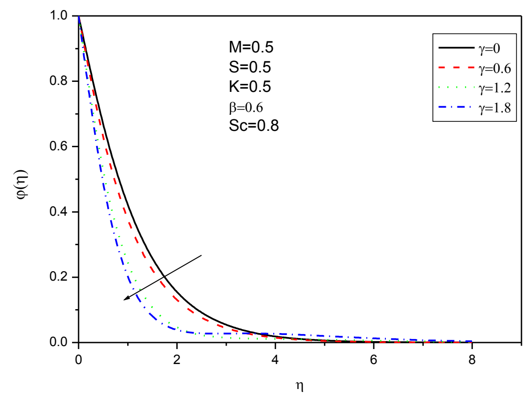

Fig 11. The influence of γ on the concentration profile

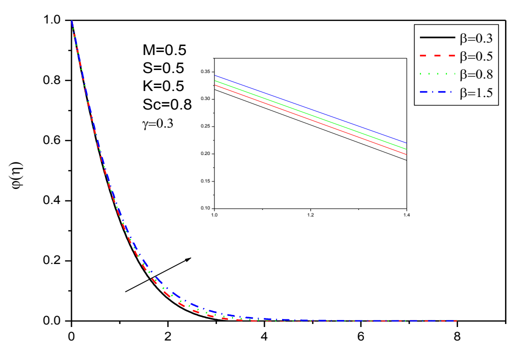

Fig 9. The influence of β on the concentration profile

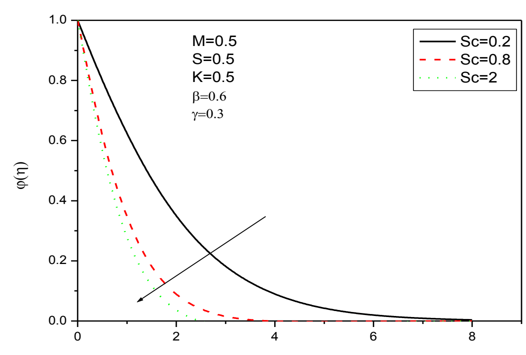

Fig 10. The influence of Sc on the concentration profile

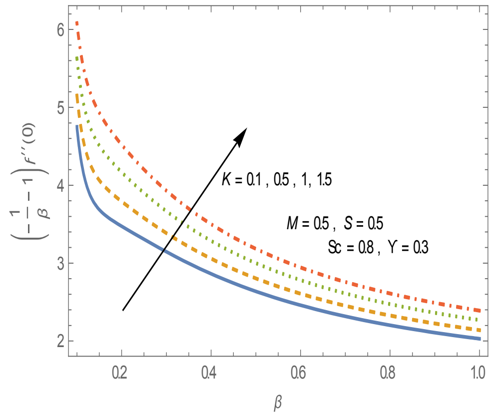

Fig-12. The influence of K Vs β on the skin friction coefficient

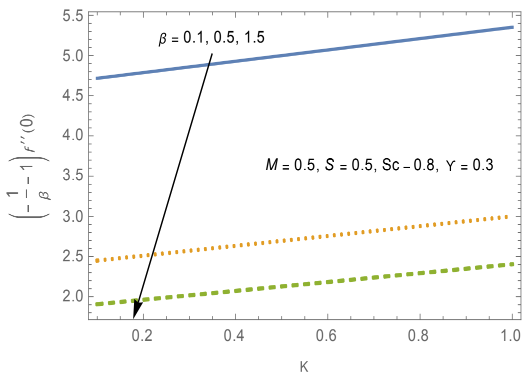

Fig-13. The influence of $\beta\ Vs\ K$ on the skin friction coefficient

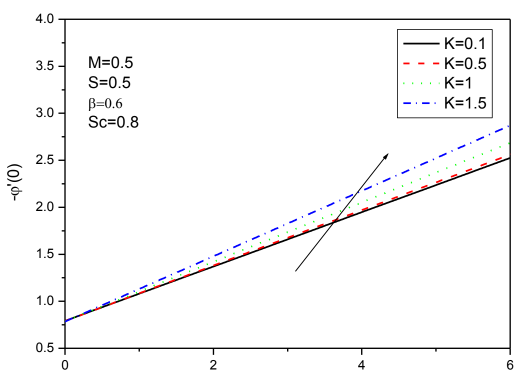

Fig 14. The influence of K Vs γ on the Sherwood number

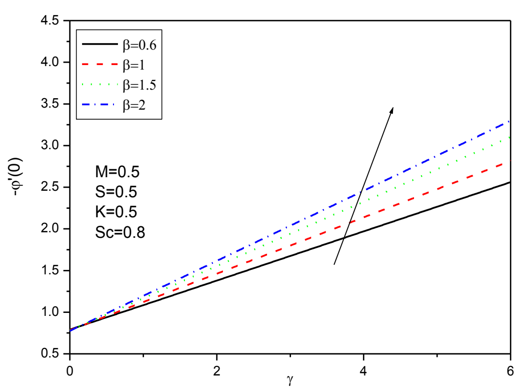

Fig 15. The influence of β Vs γ on the Sherwood number