Heat and Mass Transfer on an Unsteady MHD mixed convective Casson fluid flow past a moving vertical porous plate with effects of the Dufour and Chemical reaction

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Abstract

In this article we examined the study of the heat and mass transfer in MHD flow of a Casson fluid involved a moving vertical porous plate. The governing equations are reduces to ordinary differential equation and solved by using perturbation method. The Velocity, Temperature and Concentration distributions are shows that the graphical representwith influences of the various physical parameters are theCasson Parameter (β), Inclined angle parameter (α),Grashof number (Gr),Solutal Grashof number(Gc),Prandtl number$(\Pr)$,Magnetic field parameter (M),Heat source parameter (H), Schmidt number(Sc),Chemical reaction parameter (K_R).

Key words - *MHD, Casson fluid, Dufour effectsand Chemical reaction.*

I. INTRODUCTION

The study of heat and mass transfer with chemical reaction is of the great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. The present trend in the field of chemical reaction analysis is to give a mathematical model for the system to predict the reactor performance. Chemical reactions can be codified as either heterogeneous or homogenous processes. This depends on whether they occur at an interface or as a single phase volume reaction and the reaction rate depends on the concentration of species itself. The chemical reaction in chemical and hydrometallurgical industries requires the study of heat and mass transfer with chemical reaction. The combined heat and mass transfer with chemical reaction effects play an important role in distributions of temperature moisture over agricultural fields, formation and dispersion of fog, groves of fruit trees and designs of chemical processing equipment's.

An analytical solution for nonlinear oscillatory flow past a porous medium with radiation effects is investigated. The dimensionless governing equation for this investigation are solved analytically using two-terms harmonic and non-harmonic functions has been Considered by abdulhakeem and sathiyanathan [1]. Modather et al., Sivaraj and Rushi Kumar [2-3] has been studied a reaction is said to be first order if the rate of reaction is proportional to the concentration itself and the heat and mass transfer problem with convection boundary condition for MHD. Sivaraj and Rushikumar [4] examined the oscillatory flow investigations in a planer channel with variable temperature and concentrationshave not received much attention. Mohamed[5] explained the effects of a first order homogeneous chemical reaction, thermal radiation, heat source and thermal diffusion on the unsteady MHD double-diffusion free convection fluid flow past a vertical porous plate in the presence of mass blowing or suction.

Ibrahim etal.[6] studied the effects of radiation absorption mass diffusion, chemical reaction and heat source parameter of heat generating fluid past a vertical porous plate subjected to variable suction. Patil and Kulkarni [7] explained the multiple buoyancy effects arising from the density variation caused by variation in temperature as well as concentration.Bakr [8] declared free convection heat and mass transfer adjacent to moving vertical porous infinite plate and the plate velocity is oscillating with time about a constant zero value. The effects of the governing parameter and material parameter on the velocity and temperature are discussed. Singh and Rakesh Kumar [9] investigated the effects of chemical reaction and heat generation/absorption on unsteady MHD free convection heat and mass transfer flow of an electrically conducting, viscous, incompressible fluid past infinite hot vertical porous plate.

MHD flow with heat transfer uses of many industrial application, effects to resolve the complex problems that very often occurred in industries. The available hydrodynamics solutions including the effects of magnetic fields which arepossible as the industrial fluids are electrically conducting by Acharaya et al. [10]. Abdel khalek [11-12] analysed the effects of heat and mass transfer in a Hydromagnetic flow of a moving permeable vertical surface and the research of MHD incompressible viscous flow has many important engineering application in device such as power generator, the cooling of reactors the design of heat exchanges and MHD accelerations. Unsteady MHD free convective flow and mass transfer through a viscous incompressible, electrically conducting fluid past an infinite vertical heat porous plate by Sharma et al.[13].The effects of the first order chemical reaction and thermal radiation on the heat and mass transfer in MHD micropolar fluid flow over a vertical moving porous plate through a porous medium in the presence of heat generation by Mohamed and Abodahab [14].

Adrian postelniu [15] proposed the simultaneous heat and mass transfer by natural convection from a vertical surface embedded in a fluid saturated Darien porous medium. Raptis andKafousias [16] explained the influence of the magnetic field on the velocity profiles and the local heat transfer rate and the viscous Hydromagnetic and thermal boundary layer of the free convective and mass transfer flow. Das et al. [17] analysed the effects of permeability variation and oscillatory suction velocity in free convective and mass transfer flow of a viscous in compressible fluid past an infinite vertical porous plate through a porous medium and the solution for velocity fluid temperature field and concentration distribution are obtained using perturbation technique. The effects of viscous dissipation mass transfer and viscous dissipation parameter viscous incompressible fluid past an infinite vertical plate subjected to constant suction by Sudheerbabu et al. [18]. The flow is assumed steady laminar and two-dimensional of the surface is maintained at a uniform temperature and concentration species and it is assumed to be infinitely long by Chamkha [19].

Flow through a porous medium has numerous engineering and geophysical application, chemical engineering for filtration and purification process by Ramana Reddy et al.[20]. Gholizadeh [21] presented the effects of temperature dependent heat source on the MHD free convection and mass transfer flow of an incompressible viscous and electrically conducting fluid past an infinite vertical porous plate when the free – stream oscillates about a constant mean. Hakiem [22] studied the unsteady two-dimensional free convection and thermal radiation flow of a viscous, incompressible and electrically conducting fluid through a highly porous medium. Dulal pal and babulaltalukdar [23] examined the mixed convection flows with simultaneous heat and mass transfer under the influence of a magnetic field and chemical reaction. The effects of radiation on heat and mass transfer in mercury and electrolytic solution past an infinite porous hot vertical plate in the presence of ohmic heating and transverse magnetic field by Chaudhary et al. [24]. Makinde and Ogulu [25] investigated the effects of temperature dependent viscous incompressible electrically conducting fluid and the governing equation of the flow a semi-empirical formula for the viscosity proportional to a linear function of temperature has been used. Transient convection fluid flow with heat flux in an infinite vertical plate with chemical mass transfer by Umanta and Murtalasani [26].

Chamkha [27] viewed the simultaneous heat and mass transfer from different geometries embedded in porous medium and moves with constant velocity in the flow direction in the presence of a transverse magnetic field. Kim [28] considered the case of a semi-infinite moving porous plate in a porous medium with the presence of pressure gradient and constant velocity in the flow direction.

In the present study of the heat and mass transfer in MHD flow of a Casson fluid involved a moving vertical porous plate. The governing equations are reduces to ordinary differential equation and solved by using perturbation method. The Velocity, Temperature and Concentration distributions are shows that the graphical represents with influences of the various physical parameters.

II. MATHEMATICAL FORMULATION

we consider the unsteady two dimensional flow of an electrically conducted, heat- absorption and chemically reacting binary fluid mixture past a moving semi- infinite vertical, stretching, porous plate subjected to time dependent slip boundary conduction at the interface of porous medium and fluid layers. The x-axis is assumed to be along the plate and the y- axis normal to the plate. A uniform transfer magnetic field of magnitude B_0 is applied in the presence of thermal and concentration buoyancy effects in the direction of y-axis. The wall $y = 0$ is maintained at constant temperature T_w and concentration C_w, higher than the ambient temperature T_∞ and ambient concentration C_∞, respectively. The rest of the properties of the fluid are assumed to be constant.

The governing equations are the investigation based on the balances of mass, linear momentum, energy and concentration species. Taking into consideration these assumptions, the equations that describe the physical situation can be written in Cartesian form as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$\frac{\partial u}{\partial t^*}+\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{1}{\rho}\frac{\partial P}{\partial x}+v\left(1+\frac{1}{\beta}\right)\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{v}{K^*}u-\frac{\sigma B_0^2}{\rho}+g\beta_T(T-T_\infty)\cos\alpha+g\beta_C(C-C_\infty)\cos\alpha \quad (2)$$

$$\frac{\partial T}{\partial t^*}+\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{K_1}{\rho C_P}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)-\frac{Q(T-T_\infty)}{\rho C_P}-\frac{1}{\rho C_P}\frac{\partial q_r}{\partial y}+\frac{Q_1(C-C_\infty)}{\rho C_P}+\frac{D_m K_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} \quad (3)$$

$$\frac{\partial C}{\partial t^*}+\left(u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}\right)=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)-K_r(C-C_\infty) \quad (4)$$

The appropriate boundary conditions for velocity involving moving plate, temperature and concentration fields are defined as

$$u=u_p,\ T=T_w+\in e^{n^*t^*}(T_w-T_\infty),\ C=C_w+\in e^{n^*t^*}(C_w-C_\infty) \text{ at } y=0 \quad (5)$$

$$u\to u_\infty=U_0\left(1+\in e^{n^*t^*}\right),\ T_w\to T_\infty,\ C_w\to C_\infty \text{ as } y\to\infty \quad (6)$$

Since the motion is two dimensional and length of the plate is large enough so all the physical variables are independent of x-axis. Therefore,

$$\frac{\partial u}{\partial x}=0 \quad (7)$$

So that the suction velocity at the plate surface is a function of time only and assuming that, the suction velocity takes the following exponential form

$$v=-V_0\left(1+\in Ae^{n^*t^*}\right) \quad (8)$$

Outside the boundary layer, equation (2) gives

$$-\frac{1}{\rho}\frac{\partial P}{\partial x}=\frac{du_\infty}{dt}+\left(\frac{\sigma B_0^2}{\rho}+\frac{v}{K^*}\right)u_\infty \quad (9)$$

So, the pressure P is independent of y.

The non-dimensional variables, the basic field of equation(2)-(4) can be expressed in non-dimensional form as

$$\frac{\partial U}{\partial t}-\left(1+A\in e^{nt}\right)\frac{\partial U}{\partial Y}=\frac{dU_\infty}{dt}+B\frac{\partial^2 U}{\partial Y^2}+N\left(U_\infty-U\right)+Gr\theta\cos\alpha+Gc\phi\cos\alpha \quad (10)$$

$$\frac{\partial \theta}{\partial t}-\left(1+\in Ae^{nt}\right)\frac{\partial \theta}{\partial Y}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial Y^2}-F_1\theta+H\phi+Du\frac{\partial^2 \phi}{\partial Y^2} \quad (11)$$

$$\frac{\partial \phi}{\partial t}-\left(1+\in Ae^{nt}\right)\frac{\partial \phi}{\partial y}=\frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2}-K_R\phi \quad (12)$$

The boundary conditions becomes

$$U=U_P,\theta=1+\in e^{nt},\phi=1+\in e^{nt} \quad \text{at} \quad Y=0 \quad (13)$$

$$U\to U_\infty=1+\in e^{nt},\theta\to 0,\phi\to 0 \quad \text{as} \quad Y\to 0 \quad (14)$$

III. METHODS OF SOLUTION

The set of partial differential equations (10)-(12) cannot be solved in the close form. However, these equations can be solved analytically by using perturbation method after them to a set of ordinary differential equations in dimensionless form. This can be done, when the amplitude of oscillations $\in\left(\in<<1\right)$ is very small, we can assume the solutions of flow velocity U, temperature θ, and concentration ϕ in the neighbourhood of the plate as

$$\mathrm{U}=f_0(Y)+\in e^{nt}f_1(Y)+o(\in^2) \quad (15)$$

$$\theta=\theta_0(Y)+\in e^{nt}\theta_1(Y)+o(\in^2) \quad (16)$$

$$\phi=\phi_0(Y)+\in e^{nt}\phi_1(Y)+o(\in^2) \quad (17)$$

Substituting (10)-(12) and equating the harmonic and non-harmonic terms, neglecting the higher order of $o(\in^2)$ and simplifying to get the following pairs of for f_0, θ_0, ϕ_0 and f_1, θ_1, ϕ_1.

$$Bf_0''(Y)+f_0'(Y)-Nf_0(Y)=-[N+Gr\cos\alpha\theta_o(Y)+Gc\cos\alpha\phi_o(Y)] \quad (18)$$

$$Bf_1''(Y)+f_1'(Y)-(N+n)f_1(Y)=-[(n+N)+Af_0'(Y)+Gr\cos\alpha\theta_1(Y)+Gc\cos\alpha\phi_1(Y)] \quad (19)$$

$$\theta_0''(Y)+pr\theta_0'(Y)-F_1pr\theta_0(Y)=-\Pr[H\phi_0(Y)+Du\phi_0''(Y)] \quad (20)$$

$$\theta_1''(Y)+pr\theta_1'(Y)-(F_1+n)pr\theta_1(Y)=-\Pr[H\phi_1(Y)+Du\phi_1''(Y)+A\theta_0''(Y)] \quad (21)$$

$$\phi_0''(Y)+Sc\phi_0'(Y)-K_RSc\phi_0(Y)=0 \quad (22)$$

$$\phi_1''(Y)+Sc\phi_1'(Y)+(K_R+n)Sc\phi_1(Y)=-ASc\phi_0(Y) \quad (23)$$

The corresponding boundary conditions are

$$f_0=U_P,\ f_1=0,\theta_0=1,\ \theta_1=1,\ \phi_1=1,\ \ \phi_1=1 \quad \text{at} \quad Y=0 \quad (24)$$

$$f_0\to 1,\ f_1\to 1,\theta_0\to 0,\theta_1\to 0,\phi_0\to 0,\ \phi_1\to 0 \quad \text{as} \quad Y\to\infty \quad (25)$$

The solutions of equations (18)-(23) with the help of the boundary conditions (24) and (25), we get

$$f_0(Y) = A_{17}e^{-\beta_1 Y} + A_{15}e^{-\beta_5 Y} + A_{18}e^{-\beta_9 Y} + 1 \quad (26)$$

$$f_1(Y) = A_{28}e^{-\beta_1 Y} + A_{29}e^{-\beta_3 Y} + A_{30}e^{-\beta_5 Y} + A_{25}e^{-\beta_7 Y} + A_{21}e^{-\beta_9 Y} + A_{31}e^{-\beta_{11} Y} + 1 \quad (27)$$

$$\theta_0(Y) = A_3 e^{-\beta_1 Y} + A_4 e^{-\beta_5 Y} \quad (28)$$

$$\theta_1(Y) = A_{11}e^{-\beta_1 Y} + A_{12}e^{-\beta_3 Y} + A_{1o}e^{-\beta_5 Y} + A_{13}e^{-\beta_7 Y} \quad (29)$$

$$\phi_0(Y) = e^{-\beta_1 Y} \quad (30)$$

$$\phi_1(Y) = A_1 e^{-\beta_1 Y} + A_2 e^{-\beta_3 Y} \quad (31)$$

Substituting the above solution (26)-(31) in (15)-(17), we get the final form of velocity, temperature and concentration distribution in the boundary layer as follows

$$U(Y,t) = [A_{17}e^{-\beta_1 Y} + A_{15}e^{-\beta_5 Y} + A_{18}e^{-\beta_9 Y} + 1] + \in e^{nt}[A_{28}e^{-\beta_1 Y} + A_{29}e^{-\beta_3 Y} + A_{30}e^{-\beta_5 Y} + A_{25}e^{-\beta_7 Y} + A_{21}e^{-\beta_9 Y} + A_{31}e^{-\beta_{11} Y} + 1] \quad (32)$$

$$\theta(Y,t) = [A_3 e^{-\beta_1 Y} + A_4 e^{-\beta_5 Y}] + \in e^{nt}[A_{11}e^{-\beta_1 Y} + A_{12}e^{-\beta_3 Y} + A_{10}e^{-\beta_5 Y} + A_{13}e^{-\beta_7 Y}] \quad (33)$$

$$\phi(Y,t) = [e^{-\beta_1 Y}] + \in e^{nt}[A_1 e^{-\beta_1 Y} + A_2 e^{-\beta_3 Y}] \quad (34)$$

We get the skin friction, Nusselt number and Sherwood number from the equations (32)-(34) as follows

$$\tau(Y,t) = \left.\frac{\partial U}{\partial Y}\right|_{Y=0}$$

$$\tau(Y,t) = -[\beta_1 A_{17} + \beta_5 A_{15} + \beta_9 A_{18}] - \in e^{nt}[\beta_1 A_{28} + \beta_3 A_{29} + \beta_5 A_{30} + \beta_7 A_{25} + \beta_9 A_{21} + \beta_{11} A_{31}] \quad (35)$$

$$Nu = \left.\frac{\partial \theta}{\partial Y}\right|_{Y=0} \quad Nu(Y,t) = -[\beta_1 A_3 + \beta_5 A_4] - \in e^{nt}[\beta_1 A_{11} + \beta_3 A_{12} + \beta_5 A_{10} + \beta_7 A_{13}] \quad (36)$$

$$Sh = \left.\frac{\partial \phi}{\partial Y}\right|_{Y=0}$$

$$Sh(Y,t) = -\beta_1 - \in e^{nt}[\beta_1 A_1 + \beta_3 A_2] \quad (37)$$

IV. RESULT AND DISCUSSION

A. *Velocity Profiles*

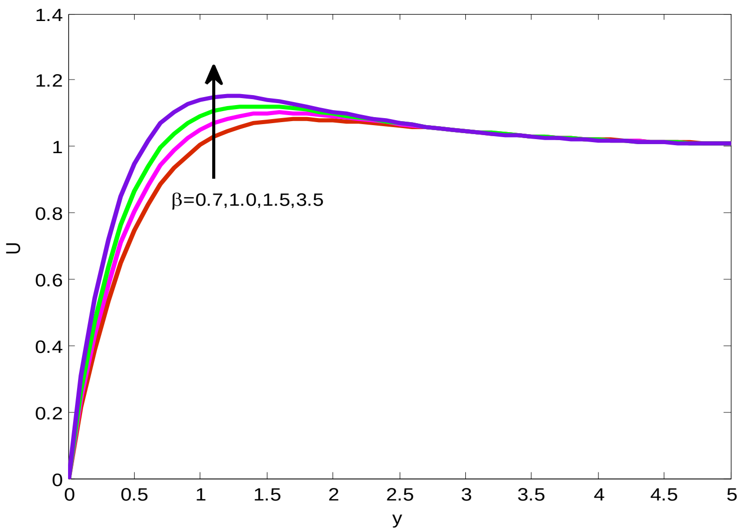

Fig.1. Influence of Casson Parameter (β) on velocity profile for(U).

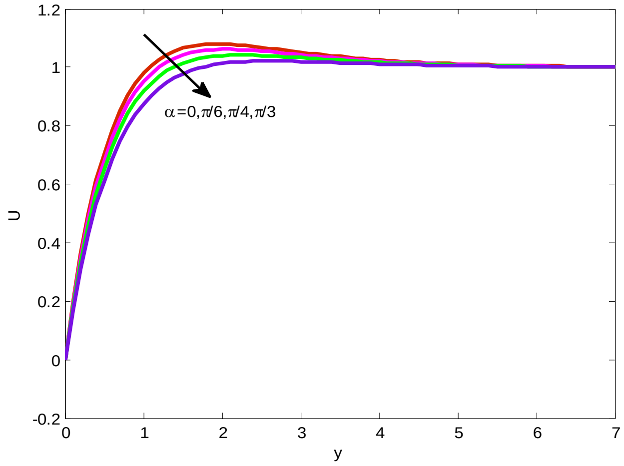

Fig.2. Influence of inclined angle parameter(α)on the velocity profile for(U).

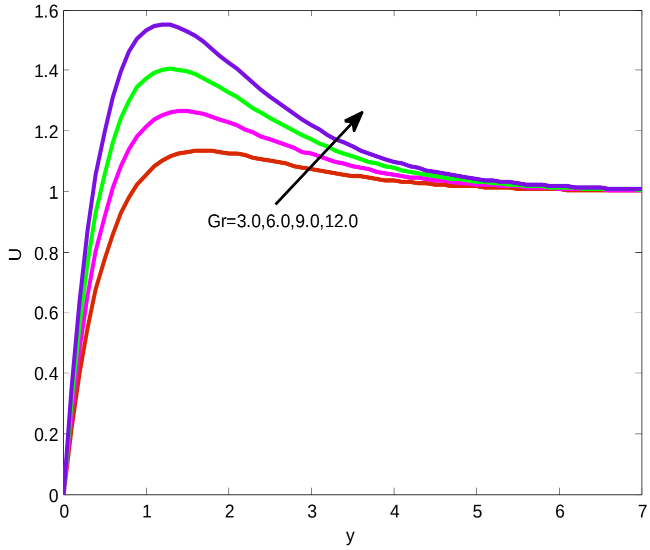

Fig.3.Influence of Grashof number (Gr)on the velocity profile for(U).

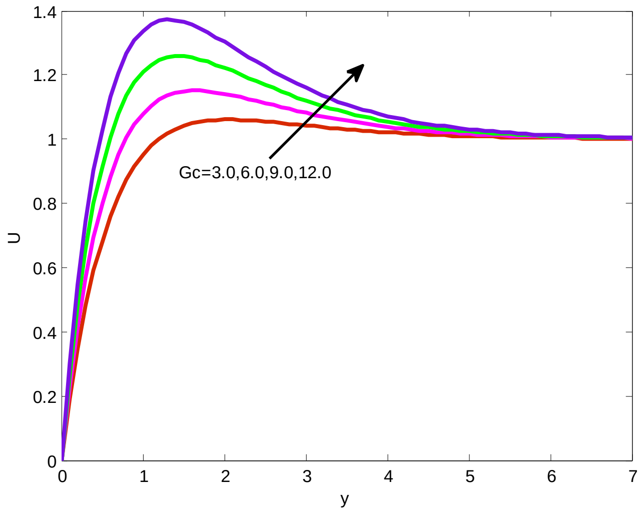

Fig.4. Influence of Solutal Grashof number (Gc) on the velocity profiles for (U).

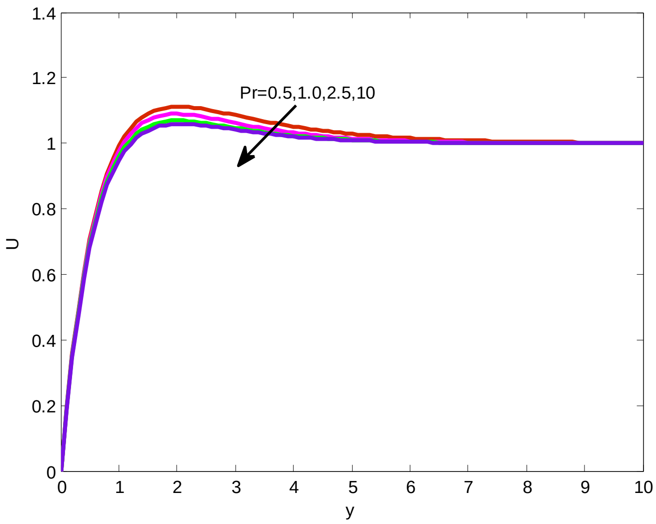

Fig.5. Influence of Prandtl number(Pr) on the velocity profile for(U).

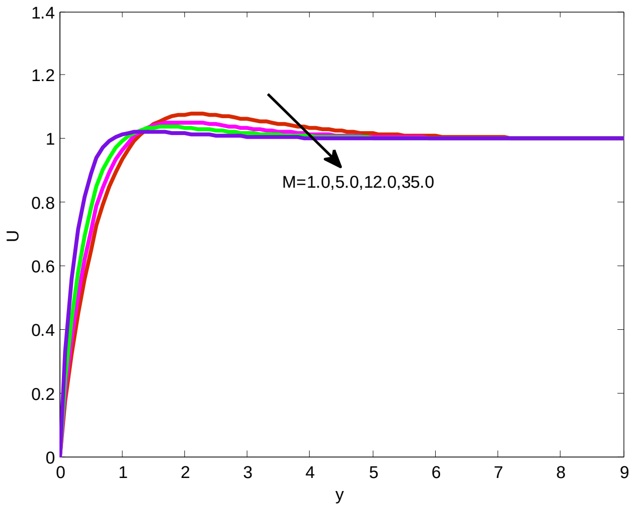

Fig.6. Influence of the Magnetic field parameter(M) on the velocity profile for(U).

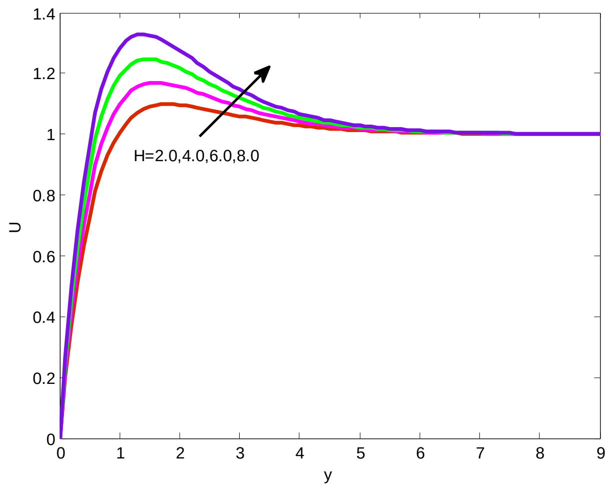

Fig.7. Influence of the Heat source parameter (H) on the velocity profile for (U).

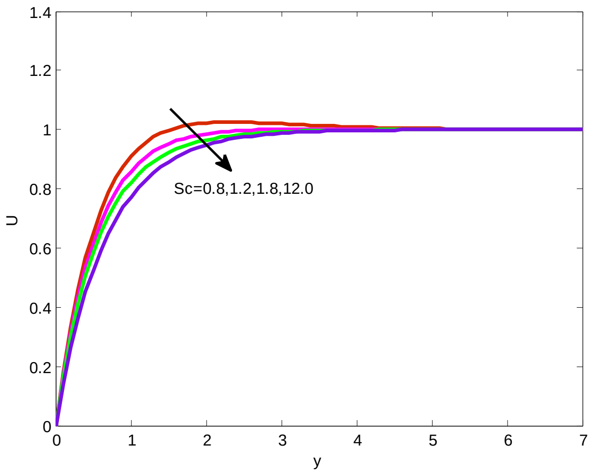

Fig.8. Influence of the Schmidt number(Sc)on the velocity profile for(U).

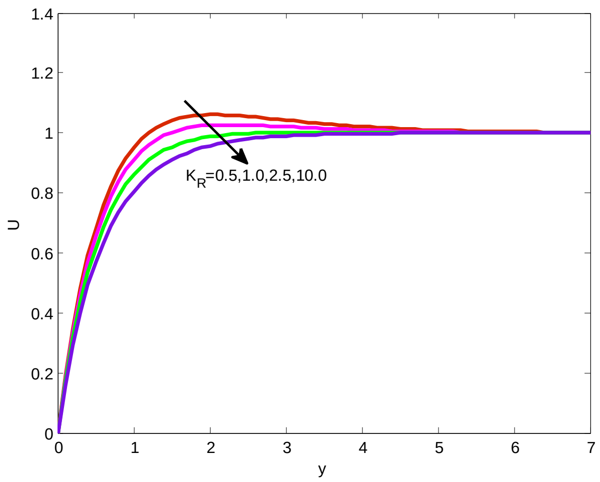

Fig.9. Influence of the chemical reaction parameter(K_R)on the velocity profile for(U)

Fig.1. shows the effects of Casson parameter (β) on velocity (U) presented given increasing value the boundary layer is increases. **Fig.2**. Illustrate the effects of inclined angle parameter (α) on the velocity (U) .It's given increasing values are produces in the boundary. **Fig.3.** is plotted to show the effects of the Grashof number (Gr) the raising influence of the Grashof number (Gr) on the velocity (U) is increases. The effect of Solutal Grashof number (Gc) is showed in **Fig.4.**and it is increasing the velocity (U) because which has tendency to decrease. The Prandtl number $(\Pr)$ decreases the velocity distribution (U) notably for its increasing and it is presented in **Fig.5.**

Fig.6.indicates the effects of the parameter (M).It is given increasing values is also enhances on the velocity profile (U). **Fig.7.** illustrate the influence of Heat source parameter (H) rising, which are produces the increase on the velocity distribution (U). **Fig.8** and **Fig.9** display the influence on the Schmidt number (Sc) and Chemical reaction parameter (K_R) respectively, as usually increase in Schmidt number (Sc) and chemical reaction parameter (k_R).

B. Temperature Profiles

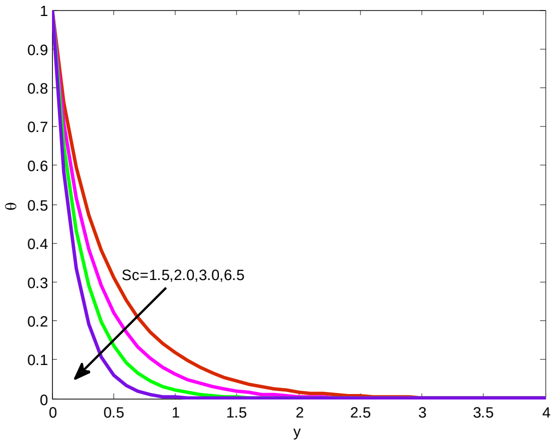

Fig.10. Influence of the Schmidt number (Sc) on the temperature profile for (θ).

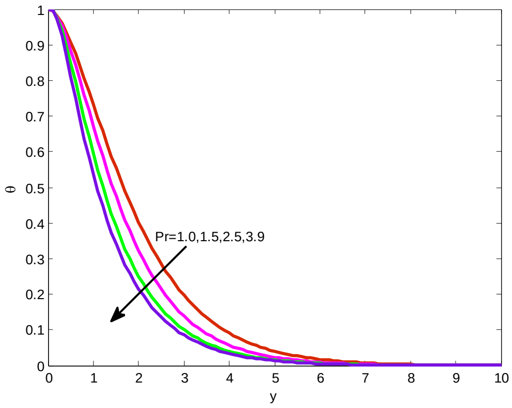

Fig.11. Influence of the Prandtl number($\Pr$) on the temperature profile for (θ).

We established the effects of Schmidt number (Sc) and Prandtl number $(\Pr)$ in temperature profiles in **Fig.10** and **Fig.11** with respect to Y. It is known the boost in Schmidt number (Sc) result in reduce on the temperature and it is observed that elevate in the Prandtl number $(\Pr)$ result in lessen on the thermal boundary layer.

C. Concentration Profiles

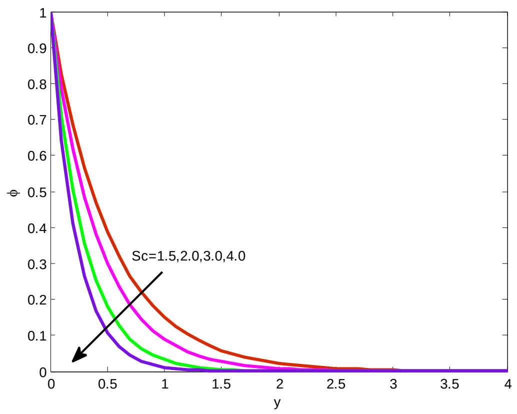

Fig.12. Influence of the Schmidt number (Sc) on the concentration profile for(ϕ).

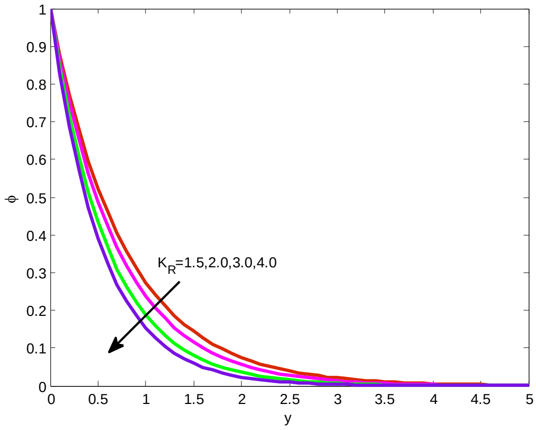

Fig.13. Influence of the chemical reaction parameter (K_R)on the concentration profile for(ϕ).

Fig.12. display the influence of Schmidt number (Sc) in the concentration profile (ϕ) with respect to Y. The concentration falls off for the increment of the Schmidt number (Sc).**Fig.13.**point out the effects of the chemical reaction parameter (K_R) on concentration ϕ in attendance given raising values the boundary layer is also reduces.

V. CONCLUSION

In the presence work, we are described the Heat and mass transfer on an unsteady MHD mixed convective Casson fluid flow past a moving vertical porous plate with effects of the Dufour and chemical reaction. We can conclude from our results for the special case of single pulse:

- The Velocity profiles of increases with increasing Casson parameter, Grashof number, Solutal Grashof number, Heat source parameter, Else otherwise the Inclined angle parameter, Prandtl number, Magnetic field parameter, Schmidt number and Chemical reaction are increasing the velocity fluid flow is decreases.
- The temperature distribution of decreases with increasing Prandtl number and Schmidt number.
- Increasing the influence of the Schmidt number and chemical reaction parameter in the concentration fluid flow is decreases.

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NOMENCLATURE

x -Dimensional distance along the plate.

y -Dimensional distances perpendicular to the plate.

u -Component of dimensional velocity u along x directions.

v -Component of dimensional velocity u along x directions.

g -Gravitational acceleration.

P -Pressure.

μ -Dynamic viscosity.

ν -Kinematic viscosity.

K^* -Dimensional porosity parameter.

σ -Magnetic permeability of the fluid.

B_o -Magnetic field coefficient.

β_T -Thermal expansion coefficient.

β_C -Concentration expansion coefficient.

T -Dimensional temperature of the fluid.

T_w -Wall temperature.

T_∞ -Ambient temperature.

C_P -Specific heat of constant pressure.

K_1 -Thermal conductivity.

Q -Dimensional heat absorption coefficient.

C -Dimensional concentration.

C_∞ -Ambient concentration.

D -Molecular diffusivity.

K_r -Chemical reaction parameter.

u_p - Moving velocity of the plate.

n^* -Dimensional positive real constant.

t^* - Dimensional time.

A -Real positive constant.

$\in$ -Small positive constant less than unity.

V_0 -Scale of suction velocity.

Gr -Grashof number.

Gr - Grashof number.

M -Magnetic field parameter.

K -Porosity parameter.

$\Pr$ -Prandtl parameter.

α -Inclined angle parameter.

Sc -Schmidt number.

K_R -Chemical reaction parameter.

U_p -Moving velocity of the plate.

τ_w -Dimensional shear stress.

Nu_x -Dimensional Nusselt number.

Re_x -Local Reynolds number.

τ - Skin friction factor.

Nu -Nusselt number.

Sh -Sherwood number.

$e_{\lambda b}$ -Plank's function.

β -Casson parameter.

D_u -Dufourparameter.

F_1 -Heat absorption parameter.

H -Heat source parameter.

APPENDIX

$$U=\frac{u}{U_0},\quad t=\frac{V_0^2 t^*}{v},\quad Y=\frac{V_0 y}{v},\quad U_\infty=\frac{u_\infty}{U_0}, M=\frac{\sigma B_0^2 v}{\rho V_0^2},\quad K=\frac{K^* V_0^2}{v}, N=M+\frac{1}{K},\quad F_1=\alpha+F,$$

$$Gr=\frac{vg\beta_T(T_w-T_\infty)}{U_0V_0^2}, Gc=\frac{vg\beta_c\left(C_w-C_\infty\right)}{U_0V_0^2}, \theta=\frac{T-T_\infty}{T_w-T_\infty}, \phi=\frac{C-C_\infty}{C_w-C_\infty},\qquad \Pr=\frac{v\rho C_P}{K_1},$$

$$\alpha=\frac{Qv}{\rho C_p V_0^2},\qquad Sc=\frac{v}{D},\qquad K_R=\frac{K_r v}{V_0^2},\qquad Du=\frac{D_m K_T\left(C_w-C_\infty\right)}{C_s C_P v(T_w-T_\infty)},\qquad \frac{\partial q_r}{\partial y}=4\left(T-T_\infty\right)I_1,$$

$$I_1=\int_0^\infty K_{\lambda w}\left(\frac{\partial e_{b\lambda}}{\partial T}\right)_w d\lambda,\qquad H=\frac{vQ_1(C_w-C_\infty)}{\rho C_P V_0^2(T_w-T_\infty)},\qquad F=\frac{4I_1 v}{\rho C_P V_0^2},\qquad B=\left(1+{}^{1}\!/\!_{\beta}\right),$$

$$\beta_1=\frac{Sc+\sqrt{Sc^2+4ScK_R}}{2}, \beta_2=\frac{-Sc+\sqrt{Sc^2+4ScK_R}}{2},\qquad \beta_3=\frac{Sc+\sqrt{Sc^2+4Sc(K_R+n)}}{2},$$

$$\beta_4=\frac{-Sc+\sqrt{Sc^2+4Sc(K_R+n)}}{2},\qquad \beta_5=\frac{\Pr+\sqrt{\Pr^2+4\Pr F_1}}{2},\qquad \beta_6=\frac{-\Pr+\sqrt{\Pr^2+4\Pr F_1}}{2},$$

$$\beta_7=\frac{\Pr+\sqrt{\Pr^2+4\Pr(F_1+n)}}{2},\qquad \beta_8=\frac{-\Pr+\sqrt{\Pr^2+4\Pr(F_1+n)}}{2}, \beta_9=\frac{1+\sqrt{1+4NB}}{2B},$$

$\beta_{10} = \dfrac{-1+\sqrt{1+4NB}}{2B}$, $\beta_{11} = \dfrac{1+\sqrt{1+4(N+n)B}}{2B}$, $\beta_{12} = \dfrac{-1+\sqrt{1+4(N+n)B}}{2B}$,

$A_1 = \dfrac{ASc\beta_1}{\beta_1^2 - Sc(\beta_1 + K_R + n)}$, $A_2 = 1 - A_1$, $A_3 = \dfrac{-\Pr(H+Du)}{\beta_1^2 - \Pr(\beta_1 + F_1)}$, $A_4 = 1 - A_3$,

$A_5 = \dfrac{-\Pr HA_1}{\beta_1^2 - \Pr(\beta_1 + F_1 + n)}$, $A_6 = \dfrac{-\Pr HA_2}{\beta_3^2 - \Pr(\beta_3 + F_1 + n)}$, $A_7 = \dfrac{-\Pr Du\beta_1^2 A_1}{\beta_1^2 - \Pr(\beta_1 + F_1 + n)}$,

$A_8 = \dfrac{-\Pr Du\beta_3^2 A_2}{\beta_3^2 - \Pr(\beta_3 + F_1 + n)}$, $A_9 = \dfrac{AA_3\beta_1 \Pr}{\beta_1^2 - \Pr(\beta_1 + F_1 + n)}$, $A_9 = \dfrac{AA_4\beta_5 \Pr}{\beta_5^2 - \Pr(\beta_5 + F_1 + n)}$,

$A_{11} = A_5 + A_7 + A_9$, $A_{12} = A_6 + A_8$, $A_{13} = 1 - \left(A_{11} + A_{12} + A_{10}\right)$, $A_{14} = \dfrac{-Gr\cos\alpha A_3}{B\beta_1^2 - (\beta_1 + N)}$

$A_{15} = \dfrac{-Gr\cos\alpha A_4}{B\beta_5^2 - (\beta_5 + N)}$, $A_{16} = \dfrac{-Gc\cos\alpha}{B\beta_1^2 - (\beta_1 + N)}$, $A_{17} = A_{14} + A_{16}$, $A_{18} = -(1 + A_{15} + A_{17})$,

$A_{19} = \dfrac{A\beta_1 A_{17}}{B\beta_1^2 - (\beta_1 + N + n)}$, $A_{20} = \dfrac{A\beta_5 A_{15}}{B\beta_5^2 - (\beta_5 + N + n)}$, $A_{21} = \dfrac{A\beta_9 A_{18}}{B\beta_9^2 - (\beta_9 + N + n)}$,

$A_{22} = \dfrac{-Gr\cos\alpha A_{11}}{B\beta_1^2 - (\beta_1 + N + n)}$, $A_{23} = \dfrac{-Gr\cos\alpha A_{12}}{B\beta_3^2 - (\beta_3 + N + n)}$, $A_{24} = \dfrac{-Gr\cos\alpha A_{10}}{B\beta_5^2 - (\beta_5 + N + n)}$,

$A_{25} = \dfrac{-Gr\cos\alpha A_{13}}{B\beta_7^2 - (\beta_7 + N + n)}$, $A_{26} = \dfrac{-Gr\cos\alpha A_1}{B\beta_1^2 - (\beta_1 + N + n)}$, $A_{27} = \dfrac{-Gr\cos\alpha A_2}{B\beta_2^2 - (\beta_2 + N + n)}$,

$A_{28} = A_{19} + A_{22} + A_{26}$ s, $A_{29} = A_{23} + A_{27}$, $A_{30} = A_{20} + A_{24}$, $A_{31} = -(1 + A_{28} + A_{29} + A_{30} + A_{25} + A_{21})$.