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Unsteady MHD Free Convection Flow Characteristics of a Viscoelastic Fluid Past a Vertical Porous Plate

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Abstract: The present study considers an analytical investigation of unsteady MHD free convection flow of a viscoelastic, incompressible, electrically conducting fluid past a vertical porous plate through a porous medium with time dependent oscillatory permeability and suction in presence of a uniform transverse magnetic field. Then effects of radiation, heat generation/ absorption, radiation absorption and homogeneous chemical reaction are considered. The novelty of the present study is to analyze the effect of time dependent fluctuate suction and permeability of the medium on a viscoelastic fluid flow in the presence of radiation, heat generation/ absorption, radiation absorption and chemical reaction. The coupled nonlinear partial differential equations are turned to ordinary by super imposing solutions with steady and time dependent transient part. Finally, the set of ordinary differential equations are solved with a perturbation scheme to meet the inadequacy of boundary condition. Elasticity of the fluid and the Lorentz force reduce the velocity and it is more pronounced in case of heavier species. Most interesting observation is the fluctuation of velocity appears near the plate due to the presence of sink and presences of elastic element as well as heat source reduce the skin friction.

Keywords: Visco elastic fluid; oscillatory flow; thermal radiation; chemical reaction; heat and mass transfer; radiation absorption; porous plate.

Nomenclature

C^*	Species concentration	σ	Electrical conductivity
D	Molecular diffusivity	ω	non-dimensional frequency of oscillation
G_r	Grash of number for heat transfer	C	non-dimensional species concentration
K_p^1	permeability of the medium	G_c	Grash of number for mass transfer
k	Thermal diffusivity	g	acceleration due to gravity
R_c	Elastic parameter	K_p	Porosity parameter
H	Heat source parameter	M	Magnetic parameter
S_h	Sherwood number	B_o	Magnetic field of uniform strength
N_u	Nusselt number	P_r	Prandtl number
T	non-dimensional temperature	S_c	Schmidt number
t	non-dimensional time	T^*	temperature of the field
u	non-dimensional velocity	t^*	time
v_0	Constant suction velocity	u^*	velocity component along x-axis

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y	non-dimensional distance along y-axis	y^*	distance along y-axis
ε	a small positive constant	ρ	Density of the field
v	Kinematic coefficient of viscosity	τ	skin friction
G_m	modified Grash of number	W	condition on the porous plate
β	volumetric coefficient of expansion of heat transfer	K_c	chemical reaction
β^*	volumetric coefficient of expansion with species concentration	R	radiation absorption

1. Introduction

An important class of two dimensional time dependent flow problem dealing with the response of boundary layer to external unsteady fluctuations of the free stream velocity about a mean value attracted the attention of many researchers. Besides that convective flow through porous medium has applications in geothermal energy recovery, thermal energy storage, oil extraction, and flow through filtering devices. Nowadays Magnetohydrodynamics is very much attracting the attention of the many authors due to its applications in geophysics and engineering. MHD flow with heat and mass transfer has been a subject of interest of many researchers because of its varied application in science and technology. Such phenomena are observed buoyancy induced motions in the atmosphere, in water bodies, quasi solid bodies such as earth, etc.

Alam et al. [1] have studied MHD Free convection heat and mass transfer flow past an inclined surface with heat generation. Makinde et al. [2] have investigated on MHD boundary layer flow and mass transfer past a vertical plate in a porous medium with constant heat flux. Misra et al. [3] analyzed bio-magnetic viscoelastic fluid flow over a stretching sheet. Aydin and Kaya [4] considered, MHD mixed convection of a viscous dissipating fluid about permeable vertical flat plate Choudary et al. [5] have investigated viscoelastic MHD boundary layer flow with heat and mass transfer over a continuously moving inclined surface in presence of energy dissipation. Palani and Abbas [6] have investigated free convection MHD flow with thermal radiation from an impulsively started vertical plate. Srinivas and Muthuraj [7] have observed MHD flow with slip effects and temperature-dependent heat source in a vertical wavy porous space. Sharma and Singh [8] have studied the effects of variable thermal conductivity and heat source/sink on MHD flow near a stagnation point on a linearly stretching sheet. Sajid et al. [9] have investigated fully developed mixed convection flow of a visco-elastic fluid between permeable parallel vertical plates. Sivraj and Kumar [10] have analyzed unsteady MHD dusty visco-elastic fluid Couette flow in an irregular channel with varying mass diffusion. Unsteady free convective MHD non-Newtonian flow through a porous medium bounded by an infinite inclined porous plate was studied by Reddy et al. [11]. Unsteady MHD free convection oscillatory Couette flow through a porous medium with periodic wall temperature was investigated by Raju and Varma [12]. Magnetic field effect on transient free convection flow through porous medium past an impulsively started vertical plate with fluctuating temperature and mass diffusion was considered by Ravikumar et al. [13].

When high temperatures attained in some engineering devices, such as, gas, for example, can be ionized and so becomes a good electrical conductor. The ionized gas or plasma that interacts with the magnetic and alters heat transfer and friction characteristic. Since, some fluids can also emit and as well as absorb thermal radiation, therefore it is of interest to study the effect of magnetic field on the temperature distribution and heat transfer when the fluid is not only an electrical conductor but also when it is capable of emitting and absorbing thermal radiation. This is of so interest because of heat transfer by thermal radiation is becoming of greater importance when we are concerned with space applications and higher operating temperatures. The growing need for chemical reactions in chemical and hydrometallurgical industries require the study of heat and mass transfer in presence chemical reaction. The presence of a foreign mass in a fluid causes some kind of chemical reaction. This can be presented either by itself or as mixtures with a fluid. In many chemical engineering practices, a chemical reaction occurs between a foreign mass and the fluid in which the plate is moving. These processes take place in several industrial applications, such as, polymer production, manufacturing of ceramics or glassware and food processing. A chemical reaction can be classified as either a homogenous or heterogeneous process that depends on whether it occurs on an interface or a single phase volume reaction.

Das and Das [14] studied MHD free convection near a moving vertical plate in the presence of thermal radiation. Deka and Neog [15] have analyzed unsteady MHD flow past a vertical oscillating plate with thermal radiation and variable mass diffusion. Abzal et al. [16] studied MHD free convection flow and mass transfer unsteady near a moving vertical plate in the presence of thermal radiation. Choudhury and Das [17] have studied MHD mixed convective heat and mass transfer in a visco elastic boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. Raptis et al. [18] have studied Radiation and free convection flow past a moving plate.

Effects of radiation in an optically thin gray gas flowing past a vertical infinite plate in the presence of a magnetic field. Chemical reaction and radiation effects on MHD free convection flow through a porous medium bounded by a vertical surface with constant heat and mass flux were studied by Reddy et al. [19]. Unsteady MHD double diffusive convection boundary-layer flow past a radiate hot vertical surface in porous media in the presence of chemical reaction and heat sink was considered by Mohammed et al. [20]. Ibrahim et al. [21] have studied Effects of chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with heat source and suction. Dash et al. [22] have studied free convective MHD flow through porous media of a rotating visco-elastic fluid past an infinite vertical porous plate with heat and mass transfer in the presence of chemical reaction. Kandasamy et al. [23] have studied Effects of chemical reaction, heat and mass transfer along a wedge with heat source and Concentration in the presence of suction or injection. Chamkha et al. [24] concentrated on similarity solution for unsteady MHD flow near a stagnation point of a three dimensional porous body with heat and mass transfer, heat generation/ absorption and chemical reaction. Magnetic field and radiation effects on a double diffusive free convective flow bounded by two infinite impermeable plates in the presence of chemical reaction were considered by Ravikumar et al. [25]. Unsteady MHD mixed convection, radiative boundary layer flow of a micro polar fluid past a semi-infinite vertical porous plate was recently studied by Mamatha et al. [27]. Effects of slip and heat transfer on the peristaltic pumping of a Williamson fluid in an inclined channel were studied by Sreenath et al. [28]. Unsteady magnetohydrodynamic free convective flow past a vertical porous plate was addressed by Murali etal. [29]. Hydromagnetic flow near a stagnation point on a stretching sheet with variable thermal conductivity and heat source/sink was investigated by Oahimire and Olajuwon [30].

Motivated by the above studies (in most of the studies a Newtonian fluid was considered), in this article we have considered an unsteady MHD free convection flow of a viscoelastic, incompressible, electrically conducting fluid past a vertical porous plate through a porous medium with time dependent oscillatory permeability and suction in presence of a uniform transverse magnetic field. The novelty of the present study is to analyze the effect of time dependent fluctuate suction and permeability of the medium on a viscoelastic fluid flow in the presence of radiation, heat generation/ absorption, radiation absorption and chemical reaction.

2. Formulation of the problem

The unsteady free convective flow of a radiative, chemically reactive, heat absorbing, viscoelastic fluid past an infinite vertical porous plate in a porous medium with time dependent oscillatory suction as well as permeability in presence of radiation absorption and a transverse magnetic field is considered. Let x*-axis be along the plate in the direction of the flow and y*-axis normal to it. Let us consider the magnetic Reynolds number is much less than unity so that induced magnetic field is neglected in comparison with the applied transverse magnetic field. The basic flow in the medium is, therefore, entirely due to the buoyancy force caused by the temperature difference between the wall and the medium. It is assumed that initially, at t* <0, the plate as well as fluids are at the same temperature and also concentration of the species is very low so that the Soret and Dofour effects are neglected. When t*, the temperature of the plate is instantaneously raised to T_w^* and the concentration of the species is set to C_w^*.

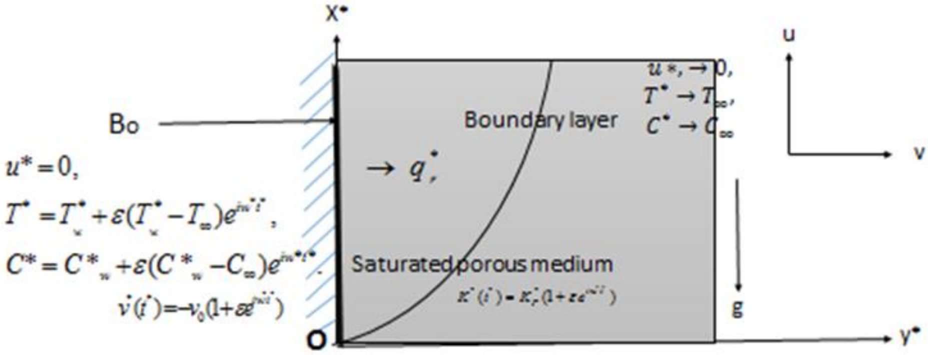

Figure 1. Flow geometry and the coordinate system

Let the permeability of the porous medium and the suction velocity be considered in the following forms respectively.

$$K^*(t^*) = K_P^*(1+\varepsilon e^{iw^*t^*}), \;\; v^*(t^*) = -v_0(1+\varepsilon e^{iw^*t^*}) \tag{1}$$

where $v_0 > 0$ and $\varepsilon \le 1$ are positive constants. Under the above assumption with usual Boussinesq's approximation, the governing equations and boundary conditions are given by

$$\frac{\partial u^*}{\partial t^*} = \vartheta \frac{\partial^2 u^*}{\partial y^{*2}} + g\beta(T^* - T_\infty^*) + g\beta^*(C^* - C_\infty^*) - \sigma B_0^2 \frac{u^*}{\rho} - \vartheta \frac{u^*}{k^*} - \frac{k_0}{\rho}\left(\frac{\partial^3 u^*}{\partial t^* \partial y^{*2}} + v^* \frac{\partial^3 u^*}{\partial y^{*3}}\right) \tag{2}$$

$$\frac{\partial T^*}{\partial t^*}\rho c_p = K \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{\partial q_r^*}{\partial y^*} - Q^*(T^* - T_\infty^*) + Q_l^*(C^* - C_\infty^*) \tag{3}$$

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - K_r(C^* - C_\infty^*) \tag{4}$$

$$u=0,\ \mathrm{T}^*=T_w+\varepsilon(T_w-T_\infty)e^{iw^*t^*},\ \mathrm{C}^*=C_w+\varepsilon(C_w-C_\infty)e^{iw^*t^*}\ \text{ at y=0,}$$
$$\mathrm{u}\to 0,\ \mathrm{T}^*\to T_\infty,\ \mathrm{C}^*\to C_\infty,\ \text{as } \mathrm{y}\to\infty \tag{5}$$

Introducing the non-dimensional quantities,

$$\mathrm{y}=\frac{v_0t^*}{\vartheta}=y,\ \mathrm{t}=\frac{v_0^2t^*}{4\vartheta},\ \mathrm{w}=\frac{4\vartheta w^*}{v_0^2},\ \mathrm{u}=\frac{u^*}{v_0},\ \mathrm{T}=\frac{T^*-T_\infty^*}{T_W-T_\infty},\ \mathrm{C}=\frac{C^*-C_\infty^*}{C_W-C_\infty},\ \mathrm{S}=\frac{\vartheta S^*}{v_0^2},\ \mathrm{K}_p=\frac{v_0^2K_P^2}{\vartheta^2},$$

$$\mathrm{M}^2=\sigma\frac{B_0^2\vartheta}{v_0^2\rho},\ \mathrm{P}_r=\frac{\vartheta}{K},\ \mathrm{S}_C=\frac{\vartheta}{D},R_C=\frac{v_0^2K_0}{\vartheta^2\rho},G_C=\frac{vg\beta^*(C_W-C_\infty)}{v_0^3},G_r=\frac{vg\beta(T_W-T_\infty)}{v_0^3}$$
$$F=\frac{4I_1\vartheta}{v_0^2\rho C_p},S=\frac{Q\vartheta}{v_0^2\rho C_p},R=\frac{Q_l\vartheta(C_W^*-C_\infty)}{v_0^2\rho(T_W^*-T_\infty)},K_C=\frac{kr\vartheta}{v_0^2} \tag{6}$$

The equations (3)-(5) reduce to following non-dimensional form

$$\frac{1}{4}\frac{\partial u}{\partial t}=\frac{\partial^2u}{\partial y^2}+G_rT+G_cC-(M^2+\frac{1}{K_p})u-\frac{1}{4}R_C\{\frac{\partial^3u}{\partial t\,\partial y^2}-4(1+\varepsilon e^{iwt})\frac{\partial^3u}{\partial y^3}\} \tag{7}$$

$$\frac{1}{4}\frac{\partial T}{\partial t}=\frac{1}{P_r}\frac{\partial^2T}{\partial y^2}-HT\ +RC \tag{8}$$

$$\frac{1}{4}\frac{\partial C}{\partial t}=\frac{1}{S_c}\frac{\partial^2C}{\partial y^2}-K_rC \tag{9}$$

$$u=0,\ \mathrm{T}\ =1+\varepsilon e^{iwt}\ ,\ \mathrm{C}\ =1+\varepsilon e^{iwt}\quad \text{at y=0,}$$
$$\mathrm{u}\to 0,\ \mathrm{T}\ \to 0,\ \mathrm{C}\ \to 0,\ \text{as } \mathrm{y}\to\infty \tag{10}$$

3. Method of solution

In view of periodic suction, temperature and concentration at the plate let us assume the velocity, temperature, concentration the neighborhood of the plate be

$$u(y,t)=u_0(y)+\varepsilon u_1(y)e^{iwt},T(y,t)=T_0(y)+\varepsilon T_1(y)e^{iwt}\text{and}C(y,t)=C_0(y)+\varepsilon C_1(y)e^{iwt} \tag{11}$$

The above method of solution has been adopted by Mishra and Shit [3], Das and Das [14] to have the periodically fluctuating flow problems.

Substituting equations (11) into (7)-(9) and comparing the nonharmonic and harmonic terms we get

$$R_Cu_0^{111}+u_0^{11}-(M^2+\frac{1}{K_P})u_0=-G_rT_0-G_cC_0 \tag{12}$$

$$R_Cu_1^{111}+u_1^{11}(1-\frac{R_Ciw}{4})-(M^2+\frac{1}{K_P}+\frac{iw}{4})u_1=-G_cC_1-G_rT_1-R_cu_0^{111} \tag{13}$$

$$T_0^{11}-P_rHT_0=-RP_rC_0 \tag{14}$$

$$T_1^{11}-(H+\frac{iw}{4})P_rT_1=-RP_rC_1 \tag{15}$$

$$C_0^{11}-K_CS_CC_0=0 \tag{16}$$

$$C_1^{11}-(K_C+\frac{iw}{4})S_CC_1=0 \tag{17}$$

The boundary conditions now reduce to

$$\begin{aligned}&u_0=u_1=0,\quad \mathrm{T}_0=T_1=1,\quad \mathrm{C}_0=C_1=1\quad \text{at y=0}\\&u_0=u_1\to 0,\quad \mathrm{T}_0=T_1\to 0,\quad \mathrm{C}_0=C_1\to 0 \text{ as y}\to\infty\end{aligned} \tag{18}$$

Equations (12) and (13) are of third order but two boundary conditions are available. Therefore the Perturbation method has been applied using R_c ($R_c<<1$), the elastic parameter as the perturbation parameter.

$$\begin{aligned}&u_0=u_{00}(y)+R_Cu_{01}(y)+o(R_C^2)\\&u_1=u_{10}(y)+R_Cu_{1\infty}(y)+o(R_C^2)\end{aligned} \tag{19}$$

Inserting equation (19) into (12) and (13) and equating the coefficients of R_C^0 and R_C to zero we have following set of ordinary differential equations.
Zeroth order equations

$$u_{00}^{11}-(M^2+\frac{1}{K_P})u_{00}=-G_cC_0-G_rT_0 \tag{20}$$

$$u_{01}^{11}-(M^2+\frac{1}{K_P})u_{01}=-u_{00}^{111} \tag{21}$$

First order equations

$$u_{10}^{11}-(M^2+\frac{1}{K_P}+\frac{iw}{4})u_{10}=-G_cC_1-G_rT_1 \tag{22}$$

$$u_{11}^{11}-(M^2+\frac{1}{K_P}+\frac{iw}{4})u_{11}=-u_{00}^{111}-u_{10}^{111}+\frac{iw}{4}u_{10}^{11} \tag{23}$$

The corresponding boundary conditions are;

$$\begin{aligned}&u_{00}=u_{01}=0,\quad \mathrm{u}_{10}=u_{11}=0,\quad \text{as y=0}\\&u_{10}=u_{11}\to 0,\quad \mathrm{u}_{00}=u_{01}\to 0,\quad \text{as y}\to\infty\end{aligned} \tag{24}$$

Solving these differential equations with the help of boundary conditions we get,

$$\begin{aligned} u(y,t) &= \{(b_4 - b_3)e^{-\sqrt{a_4 y}} + b_3 e^{-\sqrt{a_3 y}} - b_4 e^{-\sqrt{a_1 y}}\} + \\ &R_C\{b_6 - b_7)e^{-\sqrt{a_4 y}} + y b_5 e^{-\sqrt{a_4 y}} - b_6 e^{-\sqrt{a_3 y}} + b_7)e^{-\sqrt{a_1 y}}\} + \varepsilon e^{iwt} \\ &[\{(b_9 - b_8)e^{-\sqrt{a_5 y}} + b_8 e^{-\sqrt{a_2 y}} - b_9 e^{-\sqrt{a_4 y}}\} + \\ &R_C\{-(b_{10} + b_{12} - b_{13} + b_{14})e^{-\sqrt{a_5 y}} + b_{10} e^{-\sqrt{a_4 y}} + b_{12} e^{-\sqrt{a_2 y}} - b_{13} e^{-\sqrt{a_3 y}} + b_{14} e^{-\sqrt{a_1 y}}\}] \end{aligned} \tag{25}$$

$$T(y,t) = (1 - b_1)e^{-\sqrt{a_3 y}} + b_1)e^{-\sqrt{a_1 y}} + \varepsilon e^{iwt}\{(1 - b_2)e^{-\sqrt{a_4 y}} + b_2 e^{-\sqrt{a_2 y}}\} \tag{26}$$

$$C(y,t) = e^{-\sqrt{a_1 y}} + \varepsilon e^{iwt} e^{-\sqrt{a_2 y}} \tag{27}$$

The skin friction at the plate in terms of amplitude and phase angle is given by

$$\tau = \frac{\partial u_0}{\partial y}_{y=0} + \varepsilon e^{iwt} \left.\frac{\partial u_1}{\partial y}\right|_{y=0} = \left.\frac{\partial u_0}{\partial y}\right|_{y=0} + \varepsilon N \cos(wt + \alpha) \tag{28}$$

$$N = N_r + iN_i \ , \ \tan\alpha = \frac{N_i}{N_r}$$

The rate of heat transfer, i.e.heat flux at the (N_u) in terms of amplitude and phase is given by,

$$N_u = -[\frac{\partial T_0}{\partial y}_{y=0} + \varepsilon e^{iwt} \left.\frac{\partial T_1}{\partial y}\right|_{y=0}] = -[\left.\frac{\partial T_0}{\partial y}\right|_{y=0} + \varepsilon R \cos(wt + \delta)] \tag{29}$$

$$R = R_r + iR_i \ , \ \tan\delta = \frac{R_i}{R_r}$$

The mass transfer coefficient, i.e, the Sherwood number (S_h) at the plate in terms of amplitude and phase is given by

$$S_h = -[\frac{\partial C_0}{\partial y}_{y=0} + \varepsilon e^{iwt} \left.\frac{\partial C_1}{\partial y}\right|_{y=0}] = -[\left.\frac{\partial C_0}{\partial y}\right|_{y=0} + \varepsilon Q \cos(wt + \gamma)] \tag{30}$$

$$Q = Q_r + iQ_i \ , \ \tan\gamma = \frac{Q_i}{Q_r}$$

4. Results and discussion

In order to assess the effects of the dimensionless thermo physical parameters on the regime, calculations have been carried out on velocity field, temperature field, and concentration field for various physical parameters like magnetic parameter, Prandtl parameter, Grashof number, modified Grashof number, chemical reaction parameter etc. The results are represented through graphs in Figures 2 to 16. Figure 2, displays the velocity profiles for various values of magnetic parameter (M). It is noticed that the velocity decreases with an increase in M. This is due to fact that the applied magnetic field, known as Lorentz force, which acts as retarding force that condenses the momentum boundary layer. From Figure 3, it is noticed that the velocity increases with an increases in solutal Grashof number (Gc) number. This is due to the presence of mass buoyancy that enhances the fluid velocity. A similar effect is noticed from Figure 4, in the presence of Grashof number (Gr). This is due to the presence of thermal buoyancy that enhances the fluid velocity. Figure 5, depicts the effects of visco elastic parameter (Rc) on velocity, from this figure it is noticed that the velocity decreases with an increase in Rc. Influence of the frequency of oscillations (w) on velocity is presented in Figure 6, from this figure it is observed that the velocity increases with an increase in w. From Figure 7, it is seen that the velocity increases with an increase in Prandtl number (Pr). This is due to fact that when the values of Prandtl number increase, thermal conductivity of the fluid decreases, that causes the reduction in the velocity of the fluid. Effect of radiation absorption parameter (R) is presented in Figure 8. From this figure, it is noticed that the velocity decreases with an increase in R. But chemical reaction (Kc) parameter has a reverse effect on velocity as it is shown in Figure 9. This figure witnesses that velocity decreases with an increase in Kc. Effect of Schmidt number on temperature is shown in Figure 10, which concludes that that temperature decreases as the values of Sc increase. In Figure 11, effect of chemical reaction parameter (Kc) on temperature is shown, it is seen that temperature decreases as the values of Kc increase. Effect of Prandtl number (Pr) on temperature is presented in Figure 12, it is concluded that the temperature decreases as the values of Prandtl number increase. Effect of heat source parameter (H) on temperature is shown in Figure 13, from which it is concluded that the temperature decreases as H increases. From Figure 14, it is concluded that the temperature boundary layer decreases as R increases. Effect of chemical reaction parameter on concentration is presented in Figure 15, which witnesses that concentration boundary layer decreases as the values of Kc increase. Schmidt number also has the similar tendency on the concentration, which is shown in Figure 16. Effects of various parameters on skin friction, the rate of heat transfer and also the rate of mass transfer are presented in Tables 1-3. From Table 1 it is noted that skin friction increase due to an increase in Grashof number Gr. But modified Grashof number has a different effect on skin friction. Skin friction decreases due to an increase in M. From this table it is also observed that the skin friction increases due to an increase in porosity parameter. From Table 2 it is observed that skin friction increases for increasing values of R where as Nusselt number decreases with the increasing values of R. Of course skin friction, as well as Nusselt number increase for increasing values of Pr and also heat source parameter H. From Table 3, it is found that skin friction and Sherwood number both increase for increasing values of Sc, whereas skin friction decreases with increase values of Kc, but a reverse effect is noticed in the case of Sherwood number.

5. Conclusions

We have considered an unsteady MHD free convection flow of a viscoelastic, incompressible, electrically conducting fluid past a vertical porous plate through a porous medium with time dependent oscillatory permeability and suction in presence of a uniform transverse magnetic field. Some of the notable conclusions are given below.

a) Application of magnetic field decelerates the fluid flow.
b) The heavier species with low conductivity reduces the flow within the boundary layer.
c) An increase in elasticity of the fluid leads to decrease the velocity which is an established result.

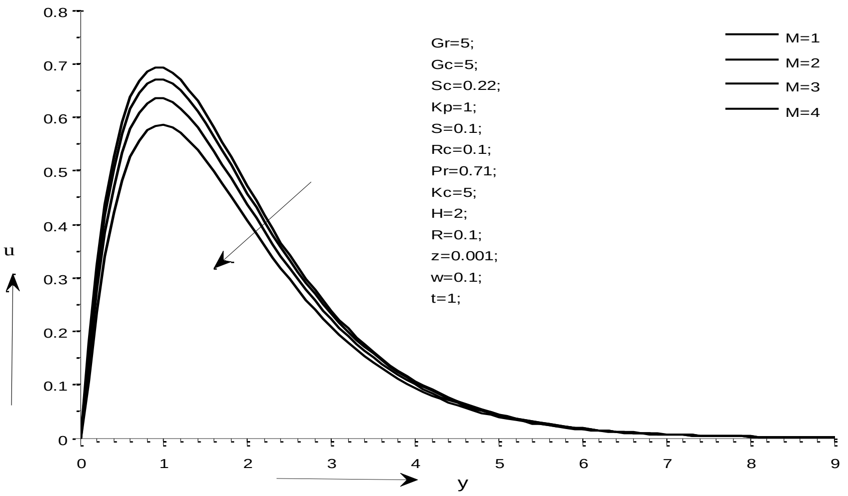

Figure 2. Effect of M on Velocity

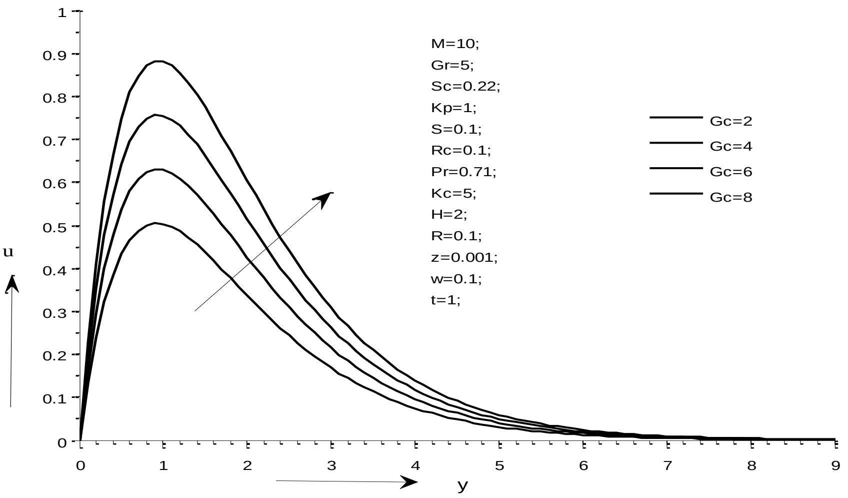

Figure 3. Effect of Gc of number on Velocity

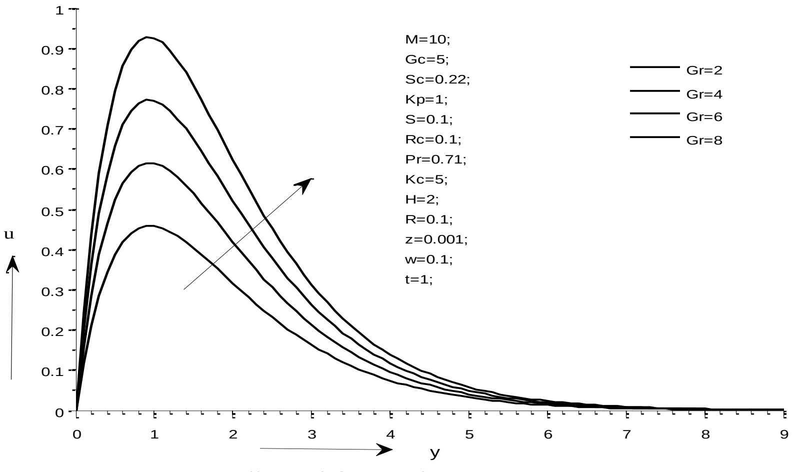

Figure 4. Effect of Grashof number on Velocity

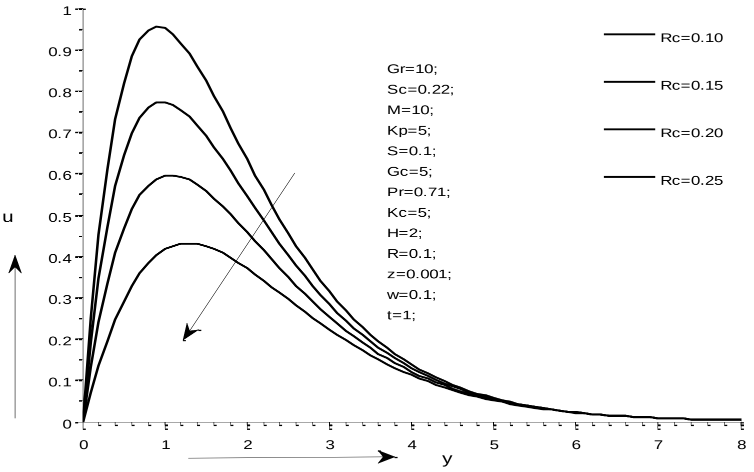

Figure 5. Effect of Rc on Velocity

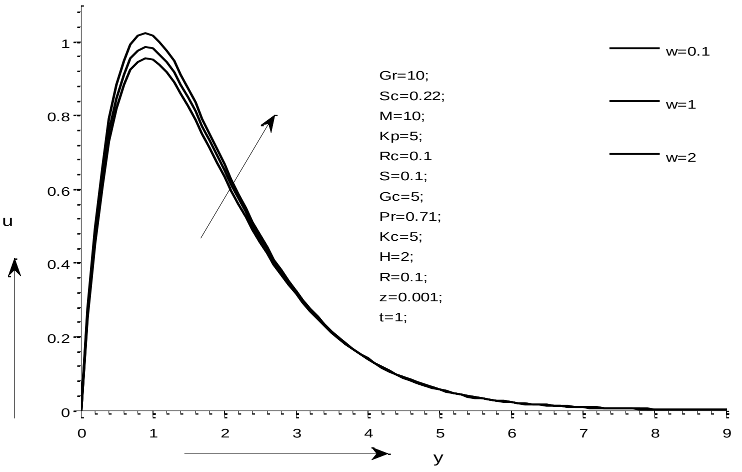

Figure 6. Effect of w on Velocity

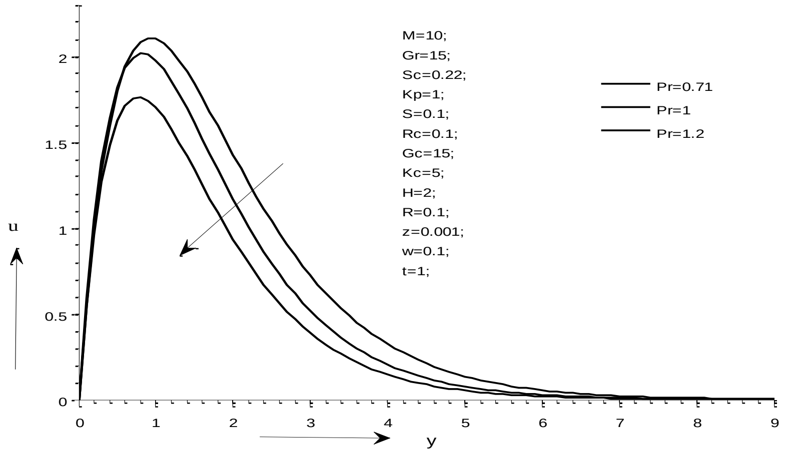

Figure 7. Effect of Pr on Velocity

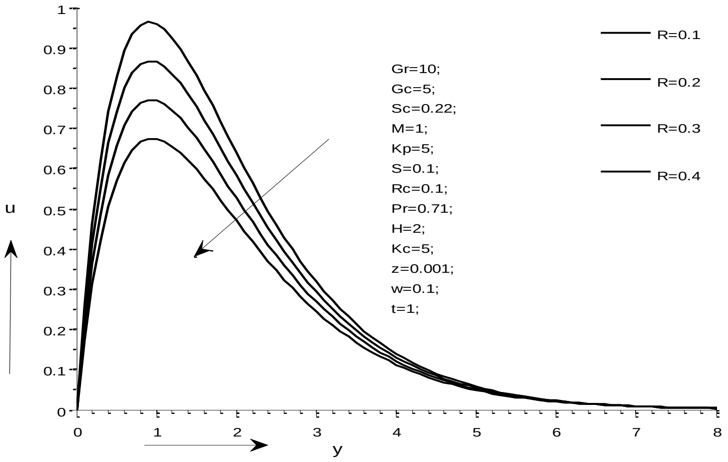

Figure 8. Effect of Ron Velocity

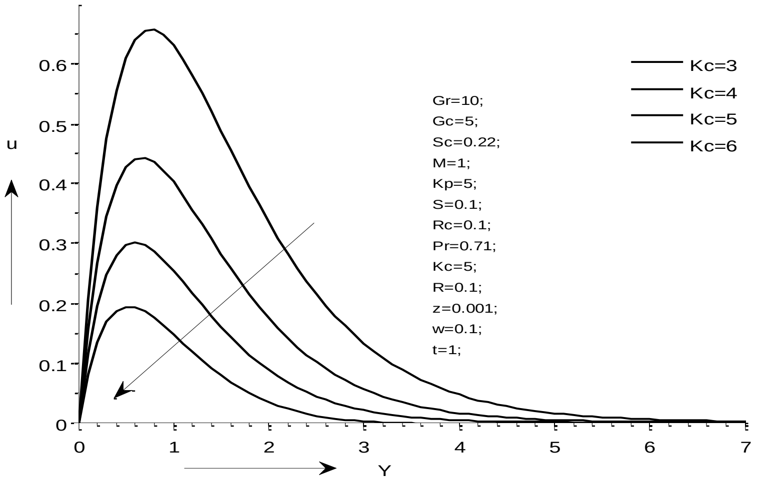

Figure 9. Effect of Kc on Velocity

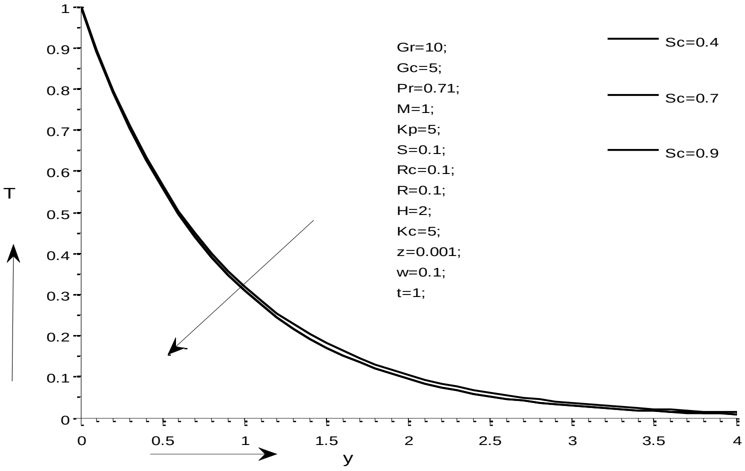

Figure 10. Effect of Sc on Temperature

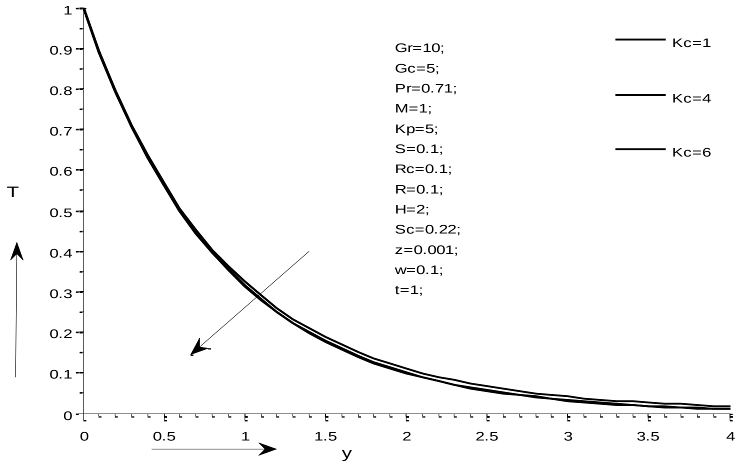

Figure 11. Effect of Kc on Temperature

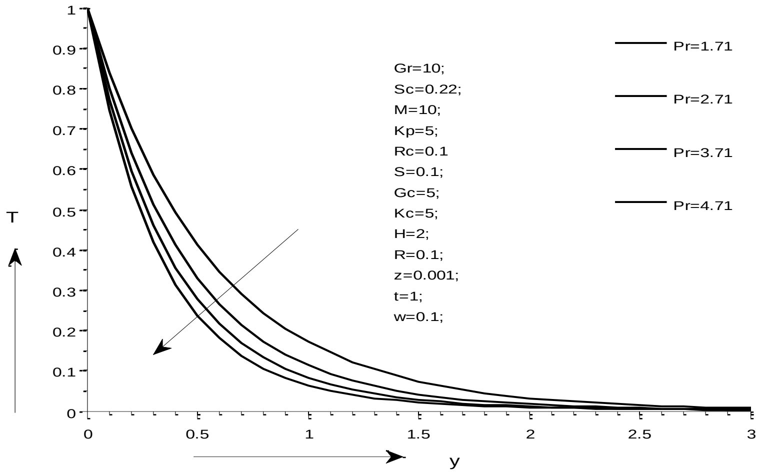

Figure 12. Effect of Prandtl number (Pr) on Temperature

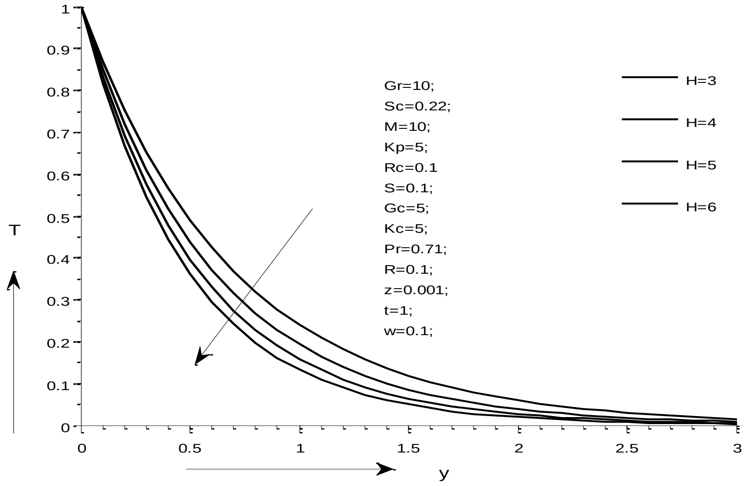

Figure 13. Effect of H on Temperature

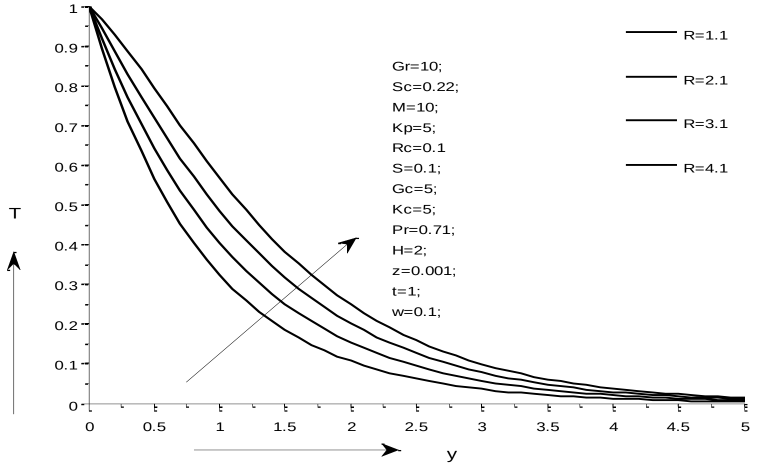

Figure 14. Effect of R on Temperature

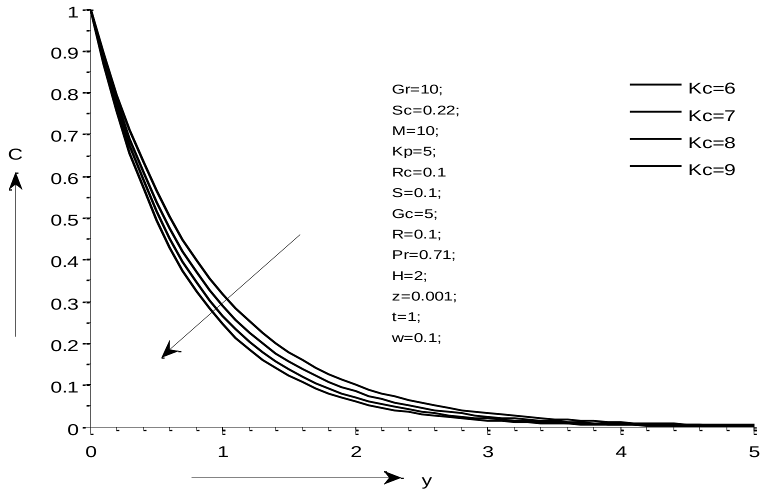

Figure 15. Effect of Kc on Concentration

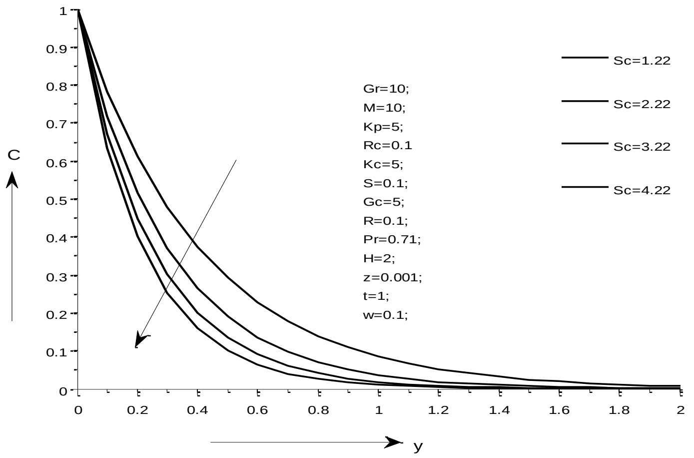

Figure 16. Effect of Schmidt number on Concentration

Table 1. Effects of Gr, Gc, M and Kp on skin friction coefficient

Gr	**Gc**	**M**	**Kp**	**τ**
10	5	1.0	1.0	12.1851
11	5	1.0	1.0	13.0855
12	5	1.0	1.0	13.9859
13	5	1.0	1.0	14.8863
10	6	1.0	1.0	13.6533
10	7	1.0	1.0	13.6452
10	8	1.0	1.0	13.6371
10	9	1.0	1.0	13.6290
10	5	2.0	1.0	13.4816
10	5	2.5	1.0	13.3871
10	5	3.0	1.0	13.2776
10	5	3.5	1.0	13.1591
10	5	1.0	0.2	8.8277
10	5	1.0	0.4	8.8304
10	5	1.0	0.6	8.8312
10	5	1.0	0.8	8.8317

Table 2. Effect of R and H on skin friction coefficient and Nusselt number

R	**Pr**	**H**	**τ**	**Nu**
1.1	0.71	2	87.7150	0.8439
2.1	0.71	2	151.7686	0.5267
3.1	0.71	2	220.8222	0.2095
4.1	0.71	2	289.8758	-0.1078
1.1	1.71	2	12.2857	1.7921
1.1	2.71	2	19.7929	2.2501
1.1	3.71	2	28.9007	2.6282
1.1	4.71	2	39.1836	2.9578
1.1	0.71	3	8.8328	1.4326
1.1	0.71	4	10.3228	1.6609
1.1	0.71	5	12.4940	1.8618
1.1	0.71	6	15.0108	2.0432

Table 3. Effect of Sc and Kc on skin friction coefficient and Sherwood number

Sc	Kc	τ	Sh
1.22	1	9.1911	2.4708
2.22	1	10.4171	3.3327
3.22	1	11.4397	4.0135
4.22	1	12.3240	4.5945
0.22	6	88.7471	1.1499
0.22	7	73.9932	1.2420
0.22	8	16.9541	1.3276
0.22	9	11.4068	1.4081

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