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AN UNSTEADY PERIODIC MIXED CONVECTION MHD FLOW OF A VISCOELASTIC FLUID THROUGH A POROUS MEDIUM IN A VERTICAL POROUS CHANNEL WITH HEAT RADIATION

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Abstract: In this paper the magnetohydrodynamic (MHD) mixed convection flow of an electrically conducting, viscoelastic and incompressible fluid through a porous medium filled in a vertical porous channel is analyzed. The fluid is injected into the channel with a constant velocity through one of the plates and simultaneously removed through the other porous plate of the channel. The flow is generated by a periodic pressure gradient varying with time. A magnetic field of uniform strength is also applied perpendicular to the plates. Closed form solution of the problem is obtained for the velocity, temperature, skin friction and the rate of heat transfer in terms of their amplitude and phase.

Keywords: Injection/suction, viscoelastic, convection, magnetohydro-dynamics (MHD), heat radiation, porous medium.

2010 Mathematics Subject Classification :76A10; 76Dxx; 76Sxx.

1. Introduction

The magnetohydrodynamic (MHD) convection flows through porous medium are of principal interest owing to their applications in geophysics, astrophysics and engineering particularly in the design of underground water energy storage systems, oil extraction, geothermal energy recovery, soil sciences etc. The knowledge of flow through porous media is useful in the recovery of crude oil efficiently from the pores of reservoir rocks by displacement with immiscible water. The wide range of industrial and technology applications of these flows has attracted the attention of large number of scholars. El-Hariem [7] has studied the magnetohydrodynamic (MHD) oscillatory free convection flow through a porous medium with constant suction velocity in the presence of heat radiation. Gholizadeh [8] investigated the MHD oscillatory flow past a vertical porous plate through porous medium in thes presence of thermal and mass diffusion with constant heat source. Aldoss et al. [2] studied Magnetohydrodynamic mixed convection from a vertical plate embedded in a porous medium. Makinde and Mhone [11] have analyzed the MHD oscillatory flow of a viscous fluid in a planer channel filled with porous medium. Alagoa et al. [1] studied the problem of radiative and free convection effects of a flow through porous medium between two infinite parallel plates with time-dependent suction. Mebine [12] studied thermal radiation effect on MHD Couette flow with heat transfer between two parallel plates. Considering the periodic wall temperature Israel-Cookey et al [10] investigated MHD oscillatory Couette flow of a radiating viscous fluid in a porous medium. Singh [17] analyzed an oscillatory convective flow through a porous medium bounded by two vertical porous plates. Attia and Ewis [4] analyzed the unsteady magnetohydrodynamic Couette flow of an electrically conducting incompressible non-Newtonian viscoelastic fluid between two parallel horizontal non-conducting porous plates with heat transfer.

The flow of viscoelastic fluids through porous media is yet another phenomenon which has attracted the attention of large number of scientists and engineers because of its importance in the flow of oil through porous rocks, the extraction of energy from geothermal regions, the filtration of solids from liquids and drug permeation through human skin. Ariel [3] obtained exact solutions of flow problems of a second grade fluid through two parallel walls. Rajgopal [15] studied the oscillatory motion of an electrically conducting viscoelastic fluid over a stretching sheet in a saturated porous medium. Gupta and Sridhar [9] analyzed the viscoelastic effects of non-Newtonian flow through porous medium. Petrov [14] analytically examined the unsteady flow of Bingham fluid caused by abruptly applied pressure gradient. Considering the constant pressure gradient Sarpkaya [16] discussed the steady flow of a uniformly conducting non-Newtonian incompressible fluid between two parallel plates. Prasuna et al. [13] examined an unsteady flow of a viscoelastic fluid through a porous medium between two impermeable parallel plates. The problem is investigated for two stages (i) when the pressure gradient is applied to attain the steady state and (ii) then the pressure gradient is suddenly withdrawn. Recently Choudhory and Das [5] studied heat transfer to MHD oscillatory viscoelastic flow in a channel with impermeable walls filled with porous medium. Singh [18] analyzed MHD mixed convection visco-elasticslip-flow through a porous medium in a vertical porous channel with thermal radiation. Singh [19] has also studied visco-elastic MHD convective periodic flow through porous medium in a rotating vertical channel with thermal radiation.

The aim of the present analysis is to study the effect of injection/suction on an unsteady mixed convection flow of a viscoelastic, incompressible and electrically conducting fluid through a porous medium in a vertical porous channel. The flow remains oscillatory due to the periodic pressure gradient considered. The magnetic field of uniform strength is applied in the direction normal to the plates. In addition, the non-uniform temperature difference of the plates is high enough to induce heat due to radiation.

2. Mathematical analysis

An unsteady periodic flow of a viscoelastic, incompressible and electrically conducting fluid through porous medium in a vertical channel is considered. The two infinite plates of the vertical channel distance 'd' apart are porous and the fluid is injected through one of the plates and simultaneously sucked through the other with the same velocity. A Cartesian coordinate system is assumed such that the X^*-axis lies vertically upwards in the direction of the buoyancy force along the centerline of the channel and Y^*-axis is perpendicular to the parallel plates. A transverse magnetic field of uniform strength B is applied along Y^*-axis. The magnetic Reynolds number is assumed very small so that the induced magnetic field is negligible. The temperature of one of the plates is non-uniform and oscillates periodically. The physical problem is schematically presented in Fig.1. All the physical quantities are independent of x^* for this problem of fully developed laminar flow. All fluid properties are assumed constant except that the influence of density variation with temperature is considered only in the body force term. Thus, under the usual Boussinesq approximation the flow of radiative fluid is governed by the following equations:

$$\frac{\partial v^*}{\partial y^*} = 0 \qquad \text{....(1)}$$

$$\frac{\partial v^*}{\partial y^*} + v^* \frac{\partial u^*}{\partial y^*} = -\frac{1\partial p^*}{\rho \partial x^*} + \nu_1 \frac{\partial^z u^*}{\partial y^{*2}} + \nu_2 \frac{\partial^z u^*}{\partial y^2 \partial t} - \frac{\sigma B_o^2}{\rho} u^* - \frac{\nu_1}{K^*} u^* + g\beta T^* \qquad \text{....(2)}$$

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{k^* \partial^z T^*}{\rho c_p \partial y^{*2}} - \frac{1\partial q^*}{\rho c_p \partial y} \qquad \text{....(3)}$$

where t* is the time, p* is the pressure, ρ is the fluid density, ν_1 is the kinematic viscosity, ν_2 is the viscoelasticity of the fluid, K* is the permeability of the porous medium, g is the acceleration due to gravity, β is the coefficient of volume expantion, k is the thermal conductivity, c_p is the specific heat at constant pressure.

Following Cogley et al [6] it is assumed that the fluid is optically thin with relatively low density and the radiative heat flux is given by

$$\frac{\partial q^*}{\partial y^*} = 4a^z T^* \qquad \text{....(4)}$$

where a is the mean radiation absorption coefficient.

The boundary conditions of the problem are

$$u^* = 0,\ v^* = V,\ T^* = T_o \cos \omega^* t^*, \quad at \quad y^* = d/2 \qquad \text{... (5)}$$

$$u^* = 0,\ v^* = V,\ T^* = o, \quad at \quad y^* = -d/2 \qquad \text{... (6)}$$

where ω^* is the frequency of oscillations. For the oscillatory internal flow in the channel, the periodic pressure gradient variations are assumed to be of the form

$$-\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} = A \cos \omega^* t^*, \text{ where A is a constant.} \qquad \text{... (7)}$$

$$y^* = d/2, u^* = 0, v^* = V, T^* = 0.$$

$$y^* = -d/2, u^* = 0, v^* = V, T_o \cos \omega^* t^* .$$

Because of the assumption of constant injection and suction velocity V at the left and the right plates respectively, continuity equation (1) integrates to

$$v^* = V. \qquad \text{...(8)}$$

Substituting equation (8) and introducing the following non-dimensional quantities

into equations (2) and (3), we get

$$x = \frac{x}{d}, \quad y = \frac{y^*}{d}, \quad u = \frac{u^*}{V}, \quad T = \frac{T^*}{T_o}, \quad t = \frac{t^* V}{d}\omega, \quad = \frac{\omega^* d}{V}. \quad p = \frac{p^*}{pV^2}, \qquad \text{.... (9)}$$

$$\lambda\left(\frac{\partial u}{\partial t} + \frac{\partial u}{\partial y}\right) = -\lambda\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial y^2} + \gamma\frac{\partial^3 u}{\partial y^2 \partial t} - M^2 u - K^{-1} u + GrT, \qquad \text{.... (10)}$$

$$\lambda\left(\frac{\partial T}{\partial t} + \frac{\partial T}{\partial y}\right) = \frac{\partial^2 Tp}{\partial y^z} - N^2 T ,$$

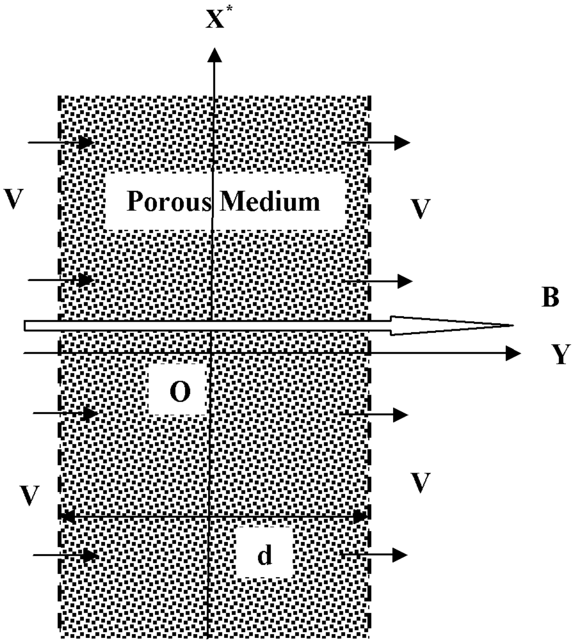

Fig. 1. Physical model of the problem with coordinate system.

where *Grashof number* $Gr = \dfrac{\partial \beta d^2 T_o}{v_1 V}$ .... (11)

Hartmann number $M = B_o d \sqrt{\dfrac{\sigma}{\rho v_1}}$

Viscoelastic parameter $\gamma = v_z \lambda / d^2$

Permeability of the porous medium $K = K^* / d^2$

Injection/suction parameter $\lambda = Vd / \nu_1$

The boundary conditions in dimensionless form become

$$u = 0, \quad T = \cos \omega t, \quad at \quad y = 1/2, \qquad \text{....(12)}$$

$$u = 0, \quad T = o, \quad at \quad y = -1/2 \qquad \text{....(13)}$$

For the mathematical solution of this unsteady MHD periodic flow in the porous channel when the fluid is also acted upon by a periodic drop in pressure, we assume the solution in complex variable notations as

$$u(y,t)=u_o(y)e^{i\omega t}, \qquad T(y,t)=\theta_o(y)e^{iwt}, -\frac{\partial p}{\partial x}=Ae^{i\omega t} \qquad \text{... (14)}$$

The real part of the solution will have physical significance.

The boundary conditions (12) and (13) can also be written in complex notations as

$$u=0, \quad T=e^{i\omega t}, \qquad at\ y=1/2, \qquad \text{....(15)}$$

$$u=0, \quad T=0, \qquad at\ y=-1/2. \qquad \text{...(16)}$$

Substituting expressions (14) into equations (10) and (11), we obtain following equations:

$$(1+i\omega\gamma)u_0'' - \lambda u_0' - (M^2+K^{-1}+i\omega\lambda)u_o = -\lambda A - Gr\theta_o, \qquad \text{..... (17)}$$

$$\theta_o'' - \lambda P\theta_o' - (N^2+i\omega\lambda\,\mathrm{Pr})\theta_o = o, \qquad \text{....(18)}$$

where the primes in these ordinary differential equations denote differentiation with respect to y. The boundary conditions (15) and (16) reduce to

$$\mathrm{u_o}=0, \ \theta_o=1, \ \text{at} \ \mathrm{y}=1/2 \qquad \text{.... (19)}$$

$$\mathrm{u_o}=0, \ \theta_o=0, \ \text{at} \ \mathrm{y}=-1/2. \qquad \text{.... (20)}$$

The solution of equation (17) for the velocity field under the boundary conditions (19) and (20) is obtained as

$$\mathrm{u(y,t)} = \mathrm{e}^{\mathrm{i}\omega \mathrm{t}}\left[\frac{\lambda \mathrm{A}}{\ell}\left\{1+\frac{\mathrm{e}^{\mathrm{my}}\sinh(\mathrm{n}/2)-\mathrm{e}^{\mathrm{ny}}\sinh(\mathrm{m}/2)}{\sin\mathrm{h}\left[(\mathrm{m}-\mathrm{n})/2\right]}\right\}+\right.$$

$$\frac{\mathrm{Gr}}{4\mathrm{in\,h}\left[(\mathrm{m}-\mathrm{n})/2\right]\sin\mathrm{h}\left[(\mathrm{r}-\mathrm{s})/2\right]}\left\{\left(\frac{\mathrm{e}^{(\mathrm{r}-\mathrm{s})/2}}{\mathrm{C}_1}-\frac{\mathrm{e}^{-(\mathrm{r}-\mathrm{s})/2}}{\mathrm{C}_2}\right)\right.$$

$$\left(e^{my-n/2}-e^{ny-m/2}\right)+\left(\frac{C_1-C_2}{C_1C_2}\right)\left(e^{my+n/z}-e^{ny-m/2}\right)e^{-\lambda pr/2}\Bigg\}$$

$$-\frac{Gr}{2\sin\ h\,[(r-s)/2]}\left(\frac{e^{ry-s/2}}{C_1}-\frac{e^{sy-r/2}}{C_2}\right)\Bigg] \qquad \ldots (21)$$

where

$C_1=(1+i\omega\gamma)r^2-\lambda r-l,\ C_2=(1+i\omega\gamma)s^2-\lambda s-l,\ l=M^2+K^{-1}+i\omega\lambda,$

$$m=\frac{\lambda+\sqrt{\lambda^2+4(1+t\omega y)}}{2(1+t\omega y)},\ n=\frac{\lambda-\sqrt{\lambda^2+4l(1+t\omega y)}}{2(1+t\omega y)},$$

$$r=\frac{\lambda\Pr+\sqrt{\lambda^z\Pr^z+4(N^2+t\omega\lambda\Pr)}}{2},\text{ and } s=\frac{\lambda\Pr-\sqrt{\lambda^z\Pr^z+4(N^2+tw\lambda\Pr)}}{2}.$$

Similarly, the solution of equation (18) for the temperature field under the boundary conditions (19) and (20) is obtained as

$$T(y,t)=\left(\frac{e^{ry-s/2}-e^{sy-r/z}}{2\sin\ h\left(r-s/2\right)}\right)e^{iwt}. \qquad \ldots\ldots.(22)$$

From the velocity field obtained in equation (21) we can get the skin-friction τ at the left plate (y = -0.5) in terms of its amplitude |F| and phase angle φ as

$$\tau=|F|\cos(t+\varphi),\mathit{with} \qquad \ldots.. (23)$$

$$F=F_jr+iF_i=\left[\frac{\lambda A}{\ell}\left(\frac{me^{-m/2}\sin\ h(n/2)-ne^{-n/2}\sin\ h(m/2)}{\sin h[(m-n)/2]}\right)\right]$$

$$+\frac{Gr}{4\sin h[(m-n)/2]\sin\ h[(r-s)/2]}\left\{\left(\frac{e^{(r-s)/2}}{C_1}-\frac{e^{-(r-s)/2}}{C_2}\right)(m-n)e^{-\lambda/2(1+t\omega\gamma)}\right.$$

$$\left.+\frac{C_1-C_2}{C_1C_2}\left(me^{-(m-n)/2}-ne^{(m-n)/2}\right)e^{-\lambda pr/2}\right\}-\frac{Gr}{2\sin\ h[(r-s)/2]}\left(\frac{r}{C_1}-\frac{s}{C_2}\right)e^{-\lambda pr/2}\Bigg] \qquad \ldots. (24)$$

The amplitude is $|F| = \sqrt{F_r^2 + F_i^2}$ and the phase angle $\varphi = \tan^{-1}\dfrac{F_i}{F_r}$ .... (25)

Similarity, we can get the Nusselt number Nu, in terms of its amplitude |H| and the phase angle ψ from equation (22) for the temperature field as

$$q = |H| \cos(t + \varphi), \qquad ....(26)$$

$$\text{with } \mathrm{H} = \mathrm{Hr} + \mathrm{i\,Hi} = \frac{(\mathrm{r}-\mathrm{s})\mathrm{e}^{-\lambda \mathrm{pr}/2}}{2\sinh\left[(\mathrm{r}-\mathrm{s})/2\right]}, \qquad ....(27)$$

where the amplitude |H| and the phase angle β of the rate of heat transfer are given

$$as\ |H| = \sqrt{Hr^z + Hi^z}.\ \psi = \tan^{-1}(Hi/Hr). \qquad ....(28)$$

The temperature field, amplitude and phase of the Nusselt number need no further discussion because these have already been discussed in detail by Singh [17].

3. Results and discussion

An exact analytical solution of the problem of mixed convection MHD flow of a viscoelastic fluid through a porous medium bounded by two infinite vertical porous plates when the pressure gradient varies periodically with time is obtained. The two porous plates are subjected to constant injection and suction and the approximation of Cogley et al [5] for the radiation heat flux is applied. Numerical evaluations of the analytical results obtained in the previous section are then illustrated through figures. The influence of each of the parameters on the velocity profiles, the amplitude and the phase of the skin-friction are depicted through these figures.

Figure 2 shows the variations of the velocity u(y, t) verses y, over the width of the channel. This figure clearly show that the velocity is maximum in the middle of the channel which leads to parabolic velocity profiles in the channel as expected. The effects of viscoelastic parameter γ, injection/suction parameter λ , Grashof number Gr,

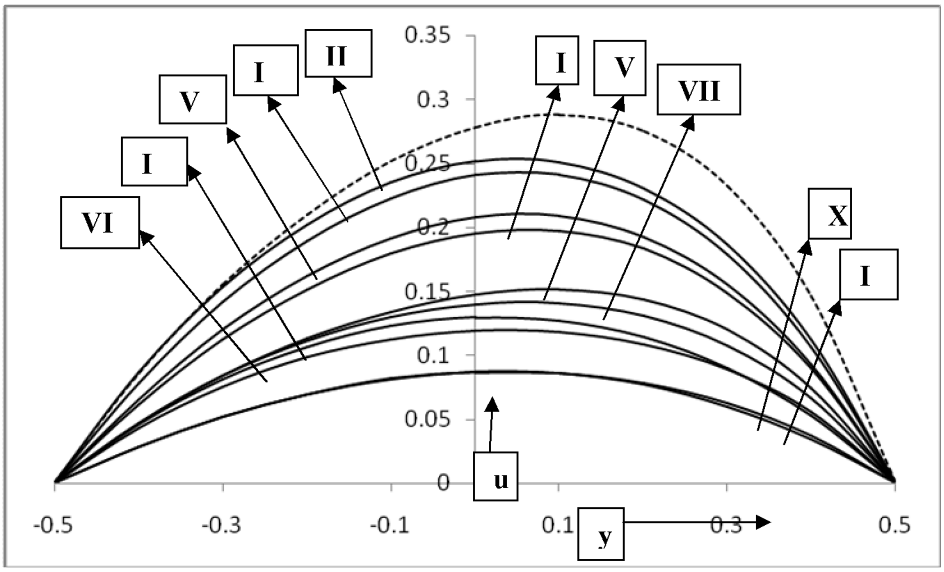

Fig.2. Velocity profiles for t=0

Table 1. The values of the parameters shown by curves in Figure 2

Curves	γ	λ	**Gr**	**M**	**K**	**Pr**	**N**	**A**	ω
	0	0.5	5	2	0.2	0.7	1	5	5
I	0.2	0.5	5	2	0.2	0.7	1	5	5
II	0.5	0.5	5	2	0.2	0.7	1	5	5
III	0.2	1	5	2	0.2	0.7	1	5	5
IV	0.2	0.5	1	2	0.2	0.7	1	5	5
V	0.2	0.5	5	4	0.2	0.7	1	5	5
VI	0.2	0.5	5	2	1	0.7	1	5	5
VII	0.2	0.5	5	2	0.2	0.7	1	5	5
VIII	0.2	0.5	5	2	0.2	0.7	5	5	5
IX	0.2	0.5	5	2	0.2	0.7	1	7	5
X	0.2	0.5	5	2	0.2	0.7	1	5	10

Hartmann number M, permeability of the porous medium K, radiation parameter N, favorable pressure gradient A and the frequency of oscillations ω are presented in Figure 2. The velocity goes on decreasing (curves I & II) with the increase of the viscoelstic parameter γ. The dotted curve corresponds to the Newtonian fluid. It means that the flow retards in the case of non-Newtonian fluids. This figure clearly shows that there is a sharp rise in the velocity (curves I & III) with the increase of the injection/suction parameter `1 . From curves I & IV it is inferred that the velocity also increases as the Grashof number Gr increases from 1 to 5. Physically it means that the enhancement of the buoyancy force leads to increase the vertical component u(y, t) of the velocity. The velocity also increases with the increase of permeability of the porous medium (curves I & VI). Physically it means that the resistance posed by the porous medium reduces as the permeability of the medium increases because of which the velocity increases. However, a decrease in velocity is observed with the increase of Hartmann number and Prandtl number(curves I & VII). This means that the increasing transverse magnetic field strength induce a drag force which tends to resist the fluid flow. Since the Prandtl number gives the relative importance of viscous dissipation to the thermal dissipation so for larger Prandtl number viscous dissipation is predominant and due to this velocity decreases. Thus, the velocity in the case of water (Pr = 7) as the fluid is less than that in the case of air (Pr = 0.7). Retaining the values of all of the parameters same and increasing only the value of the radiation parameter from 1 to 5 indicates that the velocity decreases (curves I & VIII). This figure reveals that as the pressure gradient in the channel is increased the velocity increases (curves I & X) rapidly. As expected it is due to the fact that the flow for larger pressure gradient in the channel is faster. The velocity decreases significantly (curves I & X) when the frequency of oscillations `w increases from 5 to 10 with rest of the parameters fixed.

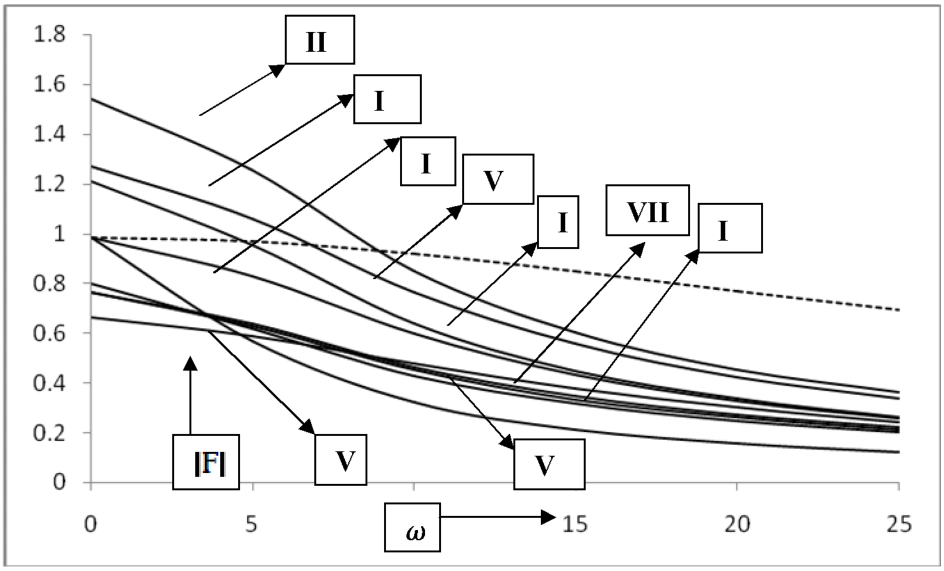

Fig.3a. Amplitude of the skin friction.

Table 2. The values of the parameters shown by curves in Figure 3a.

Curves	γ	w	G_r	M	K	Pr	N	A
…..	0	0.5	5	2	0.2	0.7	1	5
I	0.2	0.5	5	2	0.2	0.7	1	5
II	0.5	0.5	5	2	0.2	0.7	1	5
III	0.2	1	5	2	0.2	0.7	1	5
IV	0.2	0.5	1	2	0.2	0.7	1	5
V	0.2	0.5	5	4	0.2	0.7	1	5
VI	0.2	0.5	5	2	1.0	0.7	1	5
VII	0.2	0.5	5	2	0.2	0.7	1	5
VIII	0.2	0.5	5	2	0.2	0.7	5	5
IX	0.2	0.5	5	2	0.2	0.7	1	7

The variation of the amplitude |F| and the phase ϕ of the skin-friction with the increase of different parameters like the viscoelastic parameter, injection/suction parameter, Grashof number, Hartmann number M, permeability of the porous medium K, Prandtl number Pr, radiation parameter N, and the pressure gradient A are presented in Fig.3a and 3b respectively. It is obvious from

Fig.3a that for any set of parameters the amplitude goes on decreasing with the increasing frequency of oscillations `w. The skin-friction amplitude increases with the increase of injection/suction parameter ϕ, Grashof number Gr, the permeability of the porous medium K and the pressure gradient. It is true physically also because the increase in these parameters results into velocity increase which consequently leads to the enhancement of frictional force. However, the increase in viscoelastic parameter γ, Hartmann number M, Prandtl number and the radiation parameter attribute towards the decrease in the amplitude of the skin-friction.

The behavior of the phase angle `f of the skin-friction `t is shown in Fig.3b for different values of various flow parameters. From this figure it is evident that there is always a phase lag because the values of `f computed numerically remain negative throughout for any set of values of the flow parameters. We notice from Fig.3b that the phase lag increases with the increase of viscoelastic parameter, Grashof number and the permeability of the porous medium. However, the phase lag decreases with the increase of Prandtl number, injection/suction parameter, Hartmann number and the radiation parameter. This variation with the Prandtl number indicates that the phase lag is less in water (Pr = 7.0) than in air (Pr = 0.7).

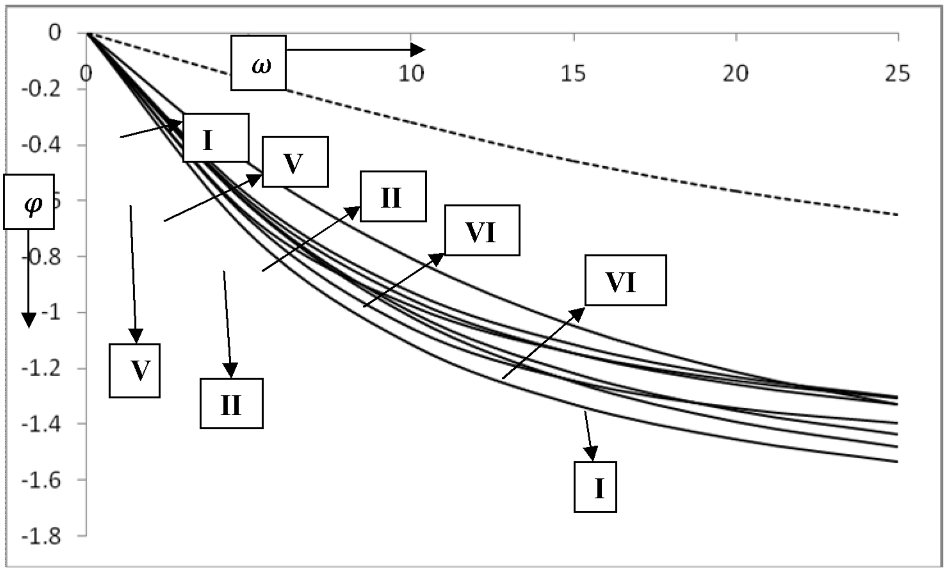

Fig.3b. Phase angle of the skin friction.

Table 3. The values of the parameters shown by curves in Figure 3b.

Curves	**γ**	**λ**	**Gr**	**M**	**K**	**Pr**	**N**	**A**
…..	0	0.5	5	2	0.2	0.7	1	5
I	0.2	0.5	5	2	0.2	0.7	1	5
II	0.2	1	5	2	0.2	0.7	1	5
III	0.2	0.5	1	2	0.2	0.7	1	5
IV	0.2	0.5	5	4	0.2	0.7	1	5
V	0.2	0.5	5	2	1.0	0.7	1	5
VI	0.2	0.5	5	2	0.2	0.7	1	5
VII	0.2	0.5	5	2	0.2	0.7	5	5
VIII	0.2	0.5	5	2	0.2	0.7	1	7

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