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EFFECT OF SLIP CONDITION ONVISCO-ELASTIC MHD OSCILLATORY FORCED CONVECTION FLOW IN A VERTICAL CHANNEL WITH HEAT RADIATION

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Abstract : In this paper an oscillatory flow of a second order viscoelastic, incompressible and electrically conducting fluid through a porous medium bounded by two infinite vertical parallel plates is carried out.One of these plates is subjected to a slip-flow condition and the other to a no-slip condition. The pressure gradient in the channel oscillates with time. A magnetic field of uniform strength is applied in the direction perpendicular to the plates. The induced magnetic field is neglected due to the assumption of small magnetic Reynolds number. The temperature difference of the two plates is also assumed high enough to induce heat transfer due to radiation. A closed form analytical solution of the problem is obtained. The analytical results are evaluated numerically and then presented graphically to discuss in detail the effects of different parameters entering into the problem. A number of particular cases have been shown by dotted curves in the figures. During the analysis it is found that the physical and the mathematical formulations of the problems by Makinde and Mhone [8], Mehmood and Ali [9], Kumar et al [6]and Choudhury and Das [3] appear to have some errors and we make the necessary corrections.

Keywords:. Oscillatory, MHD, forced convection, viscoelastic, slip-flow, porous medium.

2010 Mathematical Subject Classification: 74C10; 74C15; 74C20; 74E05; 74E20

1 Introduction

The flow of viscoelastic fluids through porous media has attracted the attention of a large number of scholars owing to their application in the fields of extraction of energy from geothermal regions and in the flow of oil through porous rocks. Many common liquids such as certain paints, polymer solutions, some organic liquids and many new materials of industrial importance exhibit both viscous and elastic properties. The fluids with such characteristics are called viscoelastic fluids. Flows through the porous medium are also very useful in chemical engineering for the processes of purification and filtration.The scientific treatmentof the problem of irrigation, soil erosion etc. are present developments of porous media.Rajgopal [15] studied the heat transfer in the forced convection flow of a visco-elastic fluid of Walter's model. Singh and Garg [20] obtained an exact solution of an oscillatory MHD flow in a rotating vertical porous channel with radiative heat. Rahman and Sarkar [12] investigated the unsteady MHD flow of a visco-elastic Oldroyd fluid under time varying body forces through a rectangular channel. Singh and Singh [19] studied MHD flow of a dusty viscoelastic (Oldroyd B-liquid)through a porous medium between two parallel plates inclined to horizon.

There are a number of technological applications where viscoelastic flows are associated. Literature is now replete with the study of non-Newtonian fluid flows for different types of geometries. Rajgopal [14] studied the flows of a non-Newtonian fluid. Rajgopal and Gupta [13] obtained an exact solution for the flow of a non-Newtonian fluid past an infinite porous plate. Ariel [1] analyzed the flow of a viscoelastic fluid past a porous plate. Labropulu [7] obtained another exact solution of non-Newtonian fluid flows with prescribed vorticity. Pillai et al [11] studied the heat transfer in a viscoelastic boundary layer flow through a porous medium. Choudhury and Das [2]investigated magnetohydrodunamic boundary layer flow of non-Newtonian fluidpast a flat plate. Samria et al. [17] analyzed free convection flow of an elasto-viscous fluid past an infinite vertical plate.

The wall slip flow is another very important phenomenon that is widely encountered in this era of industrialization. It has numerous applications, for example in lubrication of mechanical devices where a thin film of lubricant is attached to the surface slipping over one another or when the surfaces are coated with special coatings to minimize the friction between them. Marques et al [10] have considered the effect of the fluid slippage at the plate for Couette flow. Rhodes and Rouleau [16] studied the hydrodynamic lubrication of partial porous metal bearings. The problem of the slip-flow regime is very important in this era of modern science, technology and vast ranging industrialization. Hayat et al. [5] analyzed slip flow and heat transfer of a second grade fluid past a stretching sheet through a porous space. Mehmood and Ali [9] extended the problem of oscillatory MHD flow in a channel filled with porous medium studied by Makinde and Mhone [8] to slip-flow regime. Further by applying the perturbation technique Kumar et al [6] investigated the same problem of slip-flow regime for the unsteady MHD periodic flow of viscous fluid through a planer channel. Very recently, Choudhury and Das [3] studied the combined effects of magnetic field and heat radiation on a viscoelastic flow in a channel filled with porous medium. This study is also an extension of the paper by Makinde and Mhone [8].

Hence, the aim of the present study is to formulate and analyze the very important physical problem of visco-elastic, incompressible and finitely electrically conducting fluid flow through a porous medium bounded by two stationary vertical plates in the presence of heat radiation. A magnetic field ofuniform strength is applied perpendicular to the plates.During the analysis it is found that there is no consistency between the physical considerations and the mathematical formulations of the problems studied by Makinde and Mhone [8],Mehmood and Ali [9] andKumar et al [6]and the solutions obtained in all these studies are incorrect. For the visco-elastic fluid flow Choudhury and Das [3] have also adopted the geometry and the boundary conditionsof the problem as it is from Makinde and Mhone [8] without actually verifying the validity of the governing equations for the flow considered geometrically in their Fig.1.They again repeated all the mistakes of Makinde and Mhone [8].

2. Mathematical Analysis

Consider the free and forced convective MHD flow of a second order viscoelastic, incompressible and electrically conducting fluid through a porous medium in a vertical channel. The two walls of the channel are distance ‘d’ apart and the temperature of one of the walls is oscillating. A Cartesian coordinate system is introduced such that the X^*-axis lies vertically upwards along the centerline of the channel.A magnetic field of uniform strength, B_0, is applied transversely along the Y^*-axis which isperpendicular to the walls of the channel. The fluid considered is finitely conducting, and hence the magnetic Reynolds number is much less than unity (<< 1)so the induced magnetic field is negligible in comparison with the transversely applied magnetic field. The pressure gradient variation in the channel is also assumed to be oscillating in time. All the physical quantities are independent of x^* for this fully developed laminar flow. The physical problem considered is presented geometrically below in Fig.1.

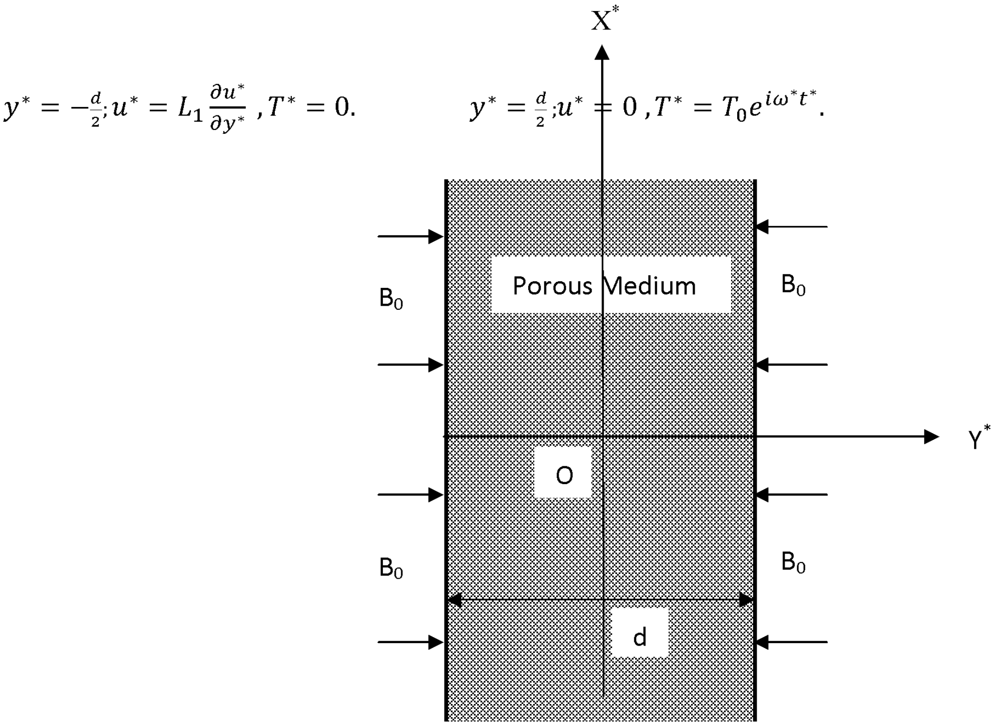

Fig.1. Geometrical presentation of the problem.

Taking in to account the usual Boussinsq's approximation, the flow is governed by the following momentum and energy equations respectively:

$$\frac{\partial u^*}{\partial t^*} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} + \vartheta_1 \frac{\partial^2 u^*}{\partial y^{*2}} + \vartheta_2 \frac{\partial^3 u^*}{\partial y^{*2}\partial t^*} - \frac{\vartheta}{K^*}u^* - \frac{\sigma B_0^2}{\rho}u^* + g\beta T^*, \quad (1)$$

$$\frac{\partial T^*}{\partial t^*} = \frac{k}{\rho c_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho c_p}\frac{\partial Q}{\partial y^*}, \quad (2)$$

with boundary conditions

$$u^* = 0, \quad T^* = T_0 e^{i\omega^* t^*} at y^* = \frac{d}{2}, \quad (3)$$

$$u^* = L_1 \frac{\partial u^*}{\partial y^*}, \quad T^* = 0 \quad at y^* = -\frac{d}{2} \quad , \quad \text{where } L_1 = \left(\frac{2-r_1}{r_1}\right)L \, . \quad (4)$$

Following Cogley et al [4] it is assumed that the fluid is optically thin with a relatively low density and the radiative heat flux is given by

$$\frac{\partial Q}{\partial y^*} = 4\alpha^2 T^*. \quad (5)$$

Now introducing the following non-dimensional quantities

$$x = \frac{x^*}{d}, y = \frac{y^*}{d}, \mathrm{u} = \frac{u^*}{U}, \mathrm{T} = \frac{T^*}{T_0}, t = \frac{t^* U}{d}, \omega = \frac{\omega^* d}{U}, p = \frac{p^*}{\rho U^2}, \quad (6)$$

in equations (1) to (4), we obtain equations in dimensionless form as

$$Re\frac{\partial u}{\partial t} = -Re\frac{\partial p}{\partial x} + (1 + i\omega\gamma)\frac{\partial^2 u}{\partial y^2} - (s^2 + H^2)u + Gr\, T\,, \quad (7)$$

$$Pe\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial y^2} - N^2\, T \;, \quad (8)$$

with boundary conditions

$$u = 0, \quad T = e^{i\omega t}, \quad at \;\; y = \frac{1}{2}, \quad (9)$$

$$u = h\frac{\partial u}{\partial y}, \quad T = 0\,, \quad at \;\; y = -\frac{1}{2}\,, \quad (10)$$

where Gr (Grashof number) = $\frac{g\beta T_0 d^2}{\vartheta U}$,

γ (Viscoelastic Parameter) = $\frac{\vartheta_2 Re}{d^2}$,

Pe (Peclet number) = $\frac{\rho c_p U d}{k}$,

Re (Reynolds number) = $\frac{Ud}{\vartheta}$,

H (Hartmann number) = $B_0 d\sqrt{\frac{\sigma}{\mu}}$,

Da (Darcy number) = $\frac{K^*}{d^2}$,

s (Porous medium shape factor parameter) = $\frac{1}{\sqrt{Da}}$,

N (Radiation parameter) = $2\alpha\frac{d}{\sqrt{k}}$,

h(Slip-flow parameter) = $\frac{L_1}{d}$.

For the oscillatory internal flow in the channel, the oscillatory pressure gradient is assumed to be of the form $-\frac{\partial p}{\partial x} = Pe^{i\omega t}$.

3. Method of solution

In order to solve (7) and (8) under the boundary conditions (9) and (10), let us assume for purely oscillatory flow

$$u(y,t) = u_0(y)e^{i\omega t},\ T(y,t) = \theta_0(y)e^{i\omega t} and -\frac{\partial p}{\partial x} = Pe^{i\omega t}. \qquad (11)$$

Substituting these expressions in (7) to (10), we obtain

$$l^2\frac{d^2u_0}{dy^2} - m^2u_0 = -PRe - Gr\theta_0 \qquad (12)$$

$$\frac{d^2\theta_0}{dy^2} - n^2\theta_0 = 0\,, \tag{13}$$

where $l = \sqrt{1 + i\omega\gamma}$, $m = \sqrt{(s^2 + H^2 + i\omega Re)}$ and $n = \sqrt{(N^2 + i\omega Pe)}$ and with transformed boundary conditions

$$u_0 = 0, \qquad \theta_0 = 1 \quad at \;\; y = \tfrac{1}{2}, \tag{14}$$

$$\mathrm{u}_0 = \mathrm{h}\frac{\partial \mathrm{u}_0}{\partial \mathrm{y}}, \qquad \theta_0 = 0 \;\; at \;\; y = -\tfrac{1}{2}. \tag{15}$$

The ordinary differential equations (12) and (13) are solved under boundary conditions (14) and (15) and the solutions for the velocity and the temperature fields are obtained, respectively, as

$$u(y,t) = \begin{bmatrix} \dfrac{PRe}{m^2}\left\{1 - \dfrac{2\,sinh\frac{m}{2l}\,cosh\frac{m}{l}y + \frac{m}{l}h\,cosh\frac{m}{l}(y+\frac{1}{2})}{\left(sinh\frac{m}{l} + \frac{m}{l}hcosh\frac{m}{l}\right)}\right\} + \dfrac{Gr}{(l^2n^2 - m^2)\,sinhn} \\ \left\{\begin{matrix} \dfrac{sinhn\,[sinh\frac{m}{l}(y+\frac{1}{2}) + \frac{m}{l}h\,cosh\frac{m}{l}(y+\frac{1}{2})] + nhsinh\frac{m}{l}(y-\frac{1}{2})}{\left(sinh\frac{m}{l} + \frac{m}{l}hcosh\frac{m}{l}\right)} \\ -sinhn(y + \frac{1}{2}) \end{matrix}\right\} \end{bmatrix} e^{i\omega t} \tag{16}$$

$$T(y,t) = \frac{sinhn(y+\frac{1}{2})}{sinhn}e^{i\omega t}. \tag{17}$$

For $\gamma = 0$ i.e. for the case of Newtonian fluid the physical problem reduces to the one studied byMehmood and Ali [9] andits correct solution for the temperature and the velocity fields are given by (17) and (18) below:

$$u(y,t) = \begin{bmatrix} \dfrac{PRe}{m^2}\left\{1 - \dfrac{2\,sinh\frac{m}{2}\,coshmy + mh\,coshm(y+\frac{1}{2})}{(sinhm + mhcoshm)}\right\} + \dfrac{Gr}{(n^2 - m^2)\,sinhn} \\ \left\{\begin{matrix} \dfrac{sinhn\,[sinhm(y+\frac{1}{2}) + mh\,coshm(y+\frac{1}{2})] + nhsinhm(y-\frac{1}{2})}{(sinhm + mhcoshm)} \\ -sinhn(y + \frac{1}{2}) \end{matrix}\right\} \end{bmatrix} e^{i\omega t}. \tag{18}$$

The solution of the problem studied by Choudhury and Das [3] can also be obtained by taking h=0, i.e. in the absence of the slip-flow condition, in (16).

By taking $\gamma = 0$ and h=0 in equation (16) the correct form of the solution of the physical problem studied by Makinde and Mhone [8] is obtained as

$$u(y,t) = \left[\frac{PRe}{m^2}\left\{1 - \frac{\cosh my}{\cosh\frac{m}{2}}\right\} + \frac{Gr}{(n^2-m^2)}\left\{\frac{\sinh m(y+\frac{1}{2})}{\sinh m} - \frac{\sinh n(y+\frac{1}{2})}{\sinh n}\right\}\right] e^{i\omega t} . \quad (19)$$

However, the solution of the energy equation for the temperature field T(y, t) remains the same.

The following limiting cases prove the validity and correctness of the analysis:

(i) For Gr = h = $\gamma = 0$ i.e.in the absence of convection currents,the slip-flow condition and for the viscous fluid in horizontal channel the solution is already obtained by Singh and Devi[21].

(ii) Further by taking s = H = 0 i.e. treating the medium in the channel as ordinary and in the absence of transverse magnetic field the solution reduces to

$$u(y,t) = \frac{P}{i\omega}\left(1 - \frac{\cosh\sqrt{i\omega Re}y}{cosh\frac{\sqrt{i\omega Re}}{2}}\right) e^{i\omega t} . \quad (20)$$

This is the dimensionless form of the very well known result reported by Schlichting and Gersten [18, p. 137].

From the velocity field in equation (16) we can obtained the skin-friction at the left wall in terms of its amplitude $|F|$ and the phase angle φ as

$$\tau_L = |F| \cos(\omega t + \varphi) , \quad (21)$$

where

$$F_r + i\,F_i = \frac{ARe}{lm}\left\{\frac{\cosh\frac{m}{l}-1}{\left(sinh\frac{m}{l} + \frac{m}{l}h\, cosh\frac{m}{l}\right)}\right\} + \frac{Gr}{(n^2-m^2)\, sinhn}\left\{\frac{m}{l}\left(\frac{sinhn + nh\, cosh\frac{m}{l}}{sinh\frac{m}{l} + \frac{m}{l}h\, cosh\frac{m}{l}}\right) - n\right\} \quad (22)$$

The amplitude and the phase angle are respectively given by

$$|F| = \sqrt{F_r^2 + F_i^2}\,, \quad \text{and}\varphi = \tan^{-1}\frac{F_i}{F_r}. \tag{23}$$

From the temperature field the rate of heat transfer Nu (Nusselt number) in terms of its amplitude and the phase angle can be obtained as

$$Nu = \left(\frac{\partial T}{\partial \eta}\right)_{\eta=-\frac{1}{2}} = |H|\cos(\omega t + \psi), \text{ where} H_r + i\,H_i = \frac{n}{\sinh n}. \tag{24}$$

The amplitude $|H|$ and the phase angle ψ of the rate of heat transfer are respectively given by

$$|H| = \sqrt{H_r^2 + H_i^2} \text{and } \psi = \tan^{-1}\frac{H_i}{H_r}. \tag{25}$$

4. Results and discussion

The problem of oscillatory convective and radiative MHD flow of a viscoelastic fluid through a porous medium in a vertical channel is analyzed under slip-flow conditions. The closed form solutions for the velocity and temperature fields are obtained and then evaluated for various values of different parameters present in the equations. To have better insight of the physical problem the variations of the physical quantities with flow parameters are shown graphically.

Fig.2 shows the variation of the velocity with the viscoelastic parameter (γ), the slip-flow parameter (h), Reynolds number (Re), Hartmann number (H), porous medium shape factor (s), pressure gradient (A) and the frequency of oscillations (ω). The dotted (….) and dashed (----) curvesrespectively represent the cases of a Newtonian fluid ($\gamma = 0$) with no-slip condition (h = 0) and slip condition($h \neq 0$). It is observed that the velocity decreases with the increase of γ i.e. the flow retards as the viscoelastic parameter increases (curves I & II). As is expected velocity increases with the increase of slip flow parameter (h). Increase in velocity is also noticed with increase of Reynols number Re, Hartmann number H, porous medium shape factor parameter s, and the pressure gradient P. The increasing Reynolds number means (being the ratio of inertial to the viscous forces) that inertial forces are predominant and strengthen the velocity field further.The increasing Hartmann number means that the increasing transverse magnetic field strength induces a drag force to the retarding flow due to the viscoelastic fluid.Similarly more favorable pressure gradient leads to faster flow. It is observed that the velocity field decreases in the left half of the channel but increases in the right half due to the increase in the Grashof number. Similarly, the increase in Peclet number and the radiation parameter lead to an increase in the left half but to a decrease in the right half of the channel. The velocity profiles also decrease with increasing frequency of oscillations .

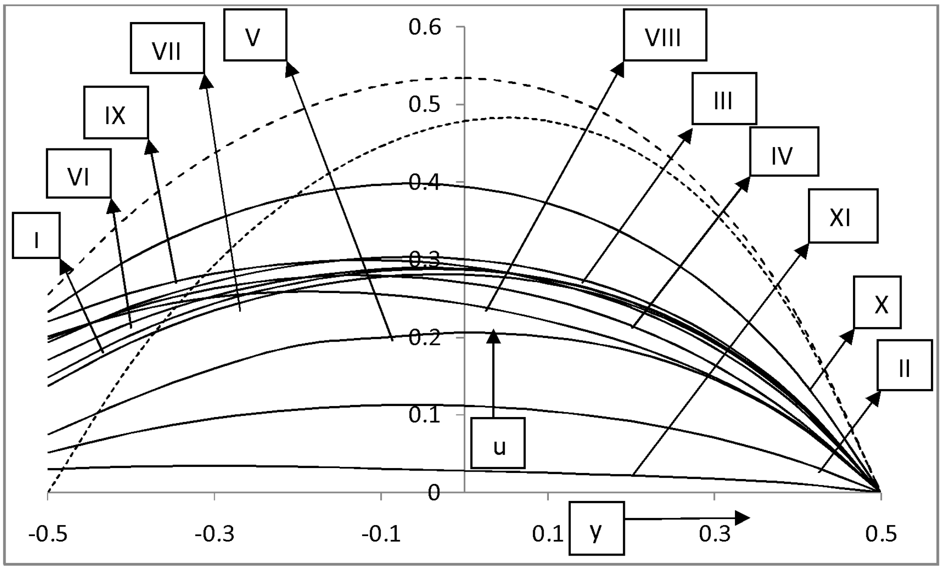

Fig.2. Velocity profiles for t=0.

Table 1.The curves in Fig.2 represent the values of parameters given in this table.

h	Gr	Re	H	s	Pe	N	P			
0	0	5	1	2	1	1	1	5	5	....
0	0.5	5	1	2	1	1	1	5	5	----
0.2	0.5	5	1	2	1	1	1	5	5	I
0.5	0.5	5	1	2	1	1	1	5	5	II
0.2	1.0	5	1	2	1	1	1	5	5	III
0.2	0.5	1	1	2	1	1	1	5	5	IV
0.2	0.5	5	0.5	2	1	1	1	5	5	V
0.2	0.5	5	1	3	1	1	1	5	5	VI
0.2	0.5	5	1	2	0.5	1	1	5	5	VII
0.2	0.5	5	1	2	1	7	1	5	5	VIII
0.2	0.5	5	1	2	1	1	5	5	5	IX
0.2	0.5	5	1	2	1	1	1	7	5	X
0.2	0.5	5	1	2	1	1	1	5	15	XI

The numerical data for the amplitude $|F|$ and the phase angle ϕ of the skin-friction τ_L at the plate (y = -0.5) with slip-flow condition are displayed in Figs.3 and 4 respectively. The effect of each parameter is ascertained through the curves keeping rest of the parameters fixed. In Fig.3 dotted curve represents the amplitude for the case of Newtonian fluid and which is maximum.Curves, I and II show clearly that the skin-friction amplitude decreases with the increase of viscoelastic parameter ν . The amplitude $|F|$ of the skin-friction also decreases with the increase of slip-flow parameter h (curves I & III). This is because of the fact that the frictional force is reduced substantially due the presence of a thin layer of lubricant on the surface. The increase of the Grashof number Gr (curves I & IV), Reynolds number Re (curves I & V) or porous medium shape factor s (curves I & VII) lead to the increases of amplitude $|F|$ of the skin-friction. This figure clearly shows that $|F|$ decreases with increasing magnetic field strength parameter, the Hartmann number H (curves I & VI). The Peclet number Pe (curves I & VIII) and the radiation parameter N (curves I & IX) lead to a decrease in the skin-friction amplitude $|F|$. Thea mplitude $|F|$ goes on decreasing with increasing values of the frequency of oscillations, ω .

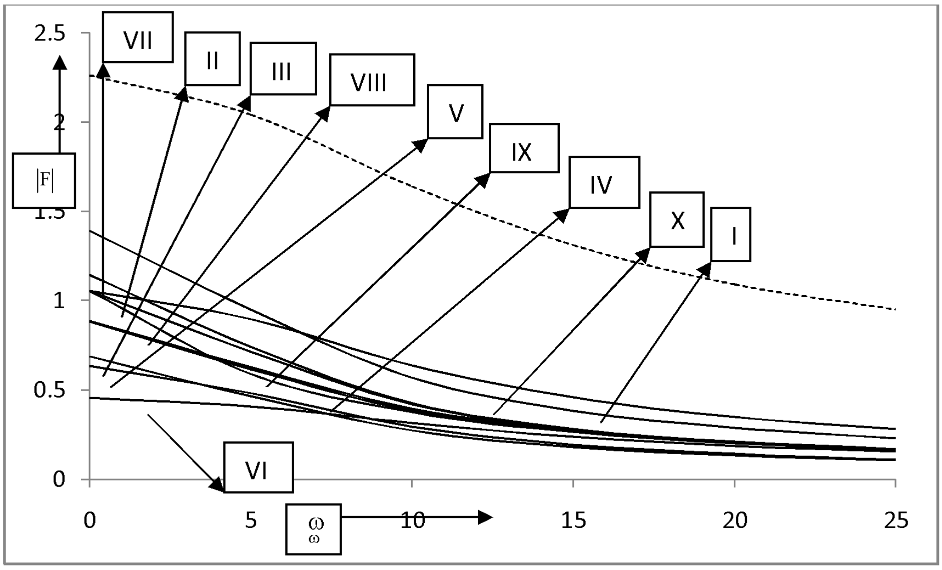

Fig.3. Amplitude of the skin friction.

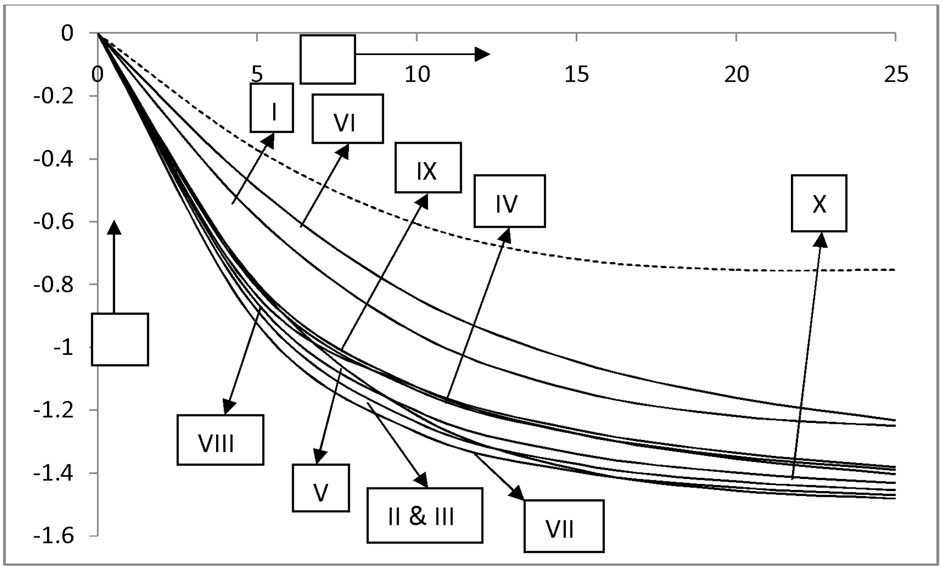

Fig.4. Phase of the skin friction.

Table 2.The curves in Figs.3 & 4 represent the values of parameters given in this table.

h	Gr	Re	H	s	Pe	N	P		
0	0.5	5	1	2	1	1	1	5	....
0.2	0.5	5	1	2	1	1	1	5	I
0.5	0.5	5	1	2	1	1	1	5	II
0.2	1.0	5	1	2	1	1	1	5	III
0.2	0.5	1	1	2	1	1	1	5	IV
0.2	0.5	5	0.5	2	1	1	1	5	V
0.2	0.5	5	1	4	1	1	1	5	VI
0.2	0.5	5	1	2	0.5	1	1	5	VII
0.2	0.5	5	1	2	1	7	1	5	VIII
0.2	0.5	5	1	2	1	1	5	5	IX
0.2	0.5	5	1	2	1	1	1	7	X

The phase angle ϕ of the skin-friction τ_L is plotted against ω in Fig.4 Since all the curves in this figure are for the negative values of ω so it means that there is always a phase lag and this phase lag goes on decreasing further with increasing frequency of oscillations ω. The increase in phase lag is quite significant with the increase of viscoelastic parameter γ (curves I & II), the slip-flow parameter h (curves I & III) and the Hartmann number H (curves I & VI) and pressure gradient A (curves I & X). However the phase lag decreases due to the increase of the Grashofnumber Gr (curves I & IV), the Reynolds number Re (curves I & V), porous medium shape factor parameter s (curves I & VII), Peclet number Pe (curves I & VIII) and radiation parameter N (curves I & IX).

Nomenclature

B	magnetic field applied
c_p	specific heat at constant pressure
Da	Darcy number
$\|F\|$	Amplitude of skin friction
g	gravitational force
Gr	Grashof number
h	slip flow parameter
H	Hartmann number
$\|H\|$	Amplitude of the rate of heat transfer
k	thermal conductivity
L_1	mean free path
N	heat radiation parameter
p	pressure
P	a constant
Pe	Peclet number
r_1	the Maxwell's reflexion coefficient.
Re	Reynolds number
t	time variable
T	fluid temperature

T_0 constant temperature

U mean flow velocity

u the axial velocity

x axial variable

y transverse variable

Greek symbols

α mean radiation absorption coefficient

β coefficient of volume expansion

γ viscoelastic parameter

ω frequency of oscillationsμ viscosity

ρ fluid density

σ electric conductivity

τ_L skin-friction at the left wall

φ phase angle of the skin-friction

ψ phase angle of rate of heat transfer

θ_0 mean non-dimensional temperature

* superscript representing dimensional quantities

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