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Flow of an Elastico-viscous Fluid Past an Infinite Plate with Variable Suction

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ABSTRACT

Unsteady state flow of an incompressible elastico-viscous fluid of second-order type past an infinite vertical porous flat plate by considering uniform and variable suction normal to the plate has been studied and an exact solution is obtained for the velocity field. In the present situation, only two prescribed boundary conditions are available while the governing equation of motion is of third-order due to the presence of elastico-viscosity parameter. The concept following Walters has been used for a much more meaningful solution. The results for the velocity distribution and skin friction have been analysed and discussed for different values of the parameters encountered in the governing equation of motion and skin friction on the plate. It is found that the effect of elastico-viscosity and suction has significant contribution on the backflow at the wall.

Keywords: Elastico-viscosity, second-order fluid, retarded history, suction parameter

NOMENCLATURE

ϕ_1	Coefficient of viscosity
ϕ_2	Coefficient of elastico–viscosity
ϕ_3	Coefficient of cross viscosity
β	Coefficient of elastico-viscosity
ρ	Density of the fluid under consideration
A_i	Dimensional form of acceleration component in the i^{th} direction
U'	Dimensional form of free stream velocity
ω_0	Dimensional form of frequency of fluctuating stream
U'_0	Dimensional form of magnification factor for free stream velocity
V'_0	Dimensional form of non zero mean suction velocity
U	Dimensional form of velocity component in the
U_i	Dimensional form of velocity component in the ith direction
T	Dimensional form of time parameter
L	Dimensional form standard length
$g(s)$	Given history
P	Indeterminate hydrostatic pressure
v'_0	Non-dimensional form of non zero mean suction velocity
u'	Non-dimensional free stream velocity

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u'_0 Non-dimensional form of magnification factor for free stream velocity

p Non-dimensional hydro static pressure parameter

t Non-dimensional time parameter

u Non-dimensional velocity component along x-direction

ω Non-dimensional form of frequency of the fluctuating stream

α Retardation factor

$g_\alpha(s)$ Retarded history

S Stress tensor

$\vec{V}$ Velocity vector

1. INTRODUCTION

The study of flows past a porous plate has wide range of applications in the fields of science, engineering, technology, biophysics, astrophysics, and space dynamics. Transpiration cooling of reentry vehicles and rocket boosters, cross hatching on the ablative surfaces, and film vaporisation in combustion chambers, are few such applications. Further, the problem assumes greater significance, especially in the chemical and nuclear reactors. In all the chemical reactors, slurry adheres to the reaction vessels and gets consolidated. As a result of which the chemical compounds within the reaction vessel percolates through the boundaries causing loss of production and consuming more reaction time. Also, the problem assumes greater importance, especially in biological systems, where the secretion through glands is involved. Many at times, the secreted fluid is not only viscous but also elastico-viscous. Therefore due to increasing importance in technological and physical problems, flow past a bounding surface with variable suction received the attention of several researchers. This motivated the study and analysis of the problem in greater detail.

Lighthill[1] initiated an important class of 2-D time-dependent flow problems dealing with the response of boundary layer to external unsteady fluctuations about a mean value. Subsequently, Soundalgekar[2] generalised the problem to account for the effects of fluctuating flow by considering the variable suction, while Agarwal and Rani[3] investigated MHD free-convection flow using numerical techniques. Later, Shah and Verma[4] examined MHD free-convection flow using the finite difference approach. The case of unsteady free-convection flow of an incompressible viscous flow past an infinite vertical plate under the influence of uniform transverse magnetic field has been examined by Sreekanth[5], *et al.* while the problem of hydromagnetic unsteady free-convection flow past an infinite porous plate using finite difference approach has been studied by Singh[6]. In all the above problems, the fluid under consideration was either Newtonian or viscous. The effect of elastico-viscosity on the flow parameters have not been studied in detail by the above investigators.

In the present analysis, the fluid under consideration is purely elastico-viscous of second order type without magnetic effects.

2. FORMULATION OF THE PROBLEM

A simple material can be defined as a substance for which stress can be determined with the entire knowledge of the history of the strain. Further, it has the property that all local states, with the same mass density, are intrinsically equal in response, with all observable differences in response being due to definite differences in the history. For any given history $g(s)$, a retarded history $g_\alpha(s)$ can be defined as:

$$g_\alpha(s) = g(\alpha s); \quad 0 < s < \infty; \quad 0 < \alpha \leq 1 \tag{1}$$

where α being termed as a retardation factor. Assuming that the stress is more sensitive to recent deformation than to the deformations at distant past, it has been proved that the theory of simple fluids yields the theory of perfect fluids as $\alpha \to 0$ and that of Newtonian fluid as a correction (up to the order of α) to theory of the perfect fluids. Neglecting all the terms of the order higher than two in α, one has incompressible second-order fluid, governed by the constitutive relation:

$$S = -PI + \phi_1 E^{(1)} + \phi_2 E^{(2)} + \phi_3 E^{(1)^2} \tag{2}$$

where, $E^{(1)}_{i,j} = U_{i,j} + U_{j,i}$ (3)

$$E_{i,j}^{(2)} = A_{i,j} + A_{j,i} + 2U_{m,i}U_{m,j} \tag{4}$$

In all the above equations, S is the stress-tensor, U_i, A_i are the components of velocity and acceleration in the direction of the i^{th} coordinate Xi, P is indeterminate hydrostatic pressure, and the coefficients ϕ_1, ϕ_2, ϕ_3, are material constants and the comma denotes covariant differentiation.

The constitutive relation for general Rivlin- Ericksen fluid also reduces to Eqn (2) when the squares and higher orders of $E^{(2)}$ are neglected, the coefficients being constants while $\phi_2 = 0$, and naming ϕ_3 as the coefficient of cross viscosity. With reference to the Rivlin-Ericksen fluids, ϕ_2 may be called as the coefficient of elastico-viscosity. It has been reported that a solution of poly-iso- butylene in cetane behaves as a second order fluid and that Markovitz determined the constants ϕ_1, ϕ_2, ϕ_3.

If $\vec{V}$ (U_1, U_2, U_3) is the velocity component then the equation of motion in X, Y and Z directions are given by

$$\rho \frac{DU_1}{DT} = \frac{\partial S_{XX}}{\partial X} + \frac{\partial S_{XY}}{\partial Y} + \frac{\partial S_{XZ}}{\partial Z} \tag{5}$$

$$\rho \frac{DU_2}{DT} = \frac{\partial S_{YX}}{\partial X} + \frac{\partial S_{YY}}{\partial Y} + \frac{\partial S_{YZ}}{\partial Z} \tag{6}$$

$$\rho \frac{DU_3}{DT} = \frac{\partial S_{ZX}}{\partial X} + \frac{\partial S_{ZY}}{\partial Y} + \frac{\partial S_{ZZ}}{\partial Z} \tag{7}$$

where $\dfrac{D}{DT} = \dfrac{\partial \vec{V}}{\partial T} + \vec{V}.\nabla \vec{V}$

A set of rectangular coordinate system has been employed with the X- axis along a 2-D infinite plane wall and Y-axis perpendicular to it. Under these conditions, the flow is independent of X. Therefore, the flow of an incompressible elastico-viscous fluid is governed by the following equations of motion and continuity.

The equation of the motion in X-direction is given by

$$\rho\left(\frac{\partial U}{\partial T} + V\frac{\partial U}{\partial Y}\right) = -\frac{\partial P}{\partial X} + \frac{\phi_1}{2}\frac{\partial^2 U}{\partial Y^2} + \phi_2\left(\frac{\partial^3 U}{\partial Y^2 \partial T} + V\frac{\partial^3 U}{\partial Y^3}\right) \tag{8}$$

The equation of the motion in Y-direction is

$$\rho\left(\frac{\partial V}{\partial T} + V\frac{\partial V}{\partial Y}\right) = -\frac{\partial P}{\partial Y} + \phi_1\frac{\partial^2 V}{\partial Y^2} + 2\phi_2\left(\frac{\partial^3 V}{\partial Y^2 \partial T} + V\frac{\partial^3 V}{\partial Y^3} + 5\frac{\partial V}{\partial Y}\frac{\partial^2 V}{\partial Y^2}\right) + \phi_3\left(\frac{\partial V}{\partial Y}\frac{\partial^2 V}{\partial Y^2}\right) \tag{9}$$

and the equation of continuity is

$$\frac{\partial V}{\partial Y} = 0 \tag{10}$$

It is evident from Eqn (10) that V is a function of time only. Therefore, in the fitness of the situation, we may consider

$$V = -V_0'(1 + \varepsilon A e^{i\omega 0T}) \tag{11}$$

where V'_0 is a non-zero constant mean suction velocity, ω_0 being the frequency parameter of the fluctuating stream, while ε is small and the suction parameter (A) is a real positive constant such that $\varepsilon A \leq 1$. The negative sign in Eqn (11) indicates that the suction velocity is normal to the plate and is directed towards the wall. In view of the above, the equations of motion are governed by

$$\rho\left(\frac{\partial U}{\partial T} - V_0'(1 + \varepsilon A e^{i\omega 0T})\frac{\partial U}{\partial Y}\right) = -\frac{\partial P}{\partial X} + \frac{\phi_1}{2}\frac{\partial^2 U}{\partial Y^2} + \phi_2\left(\frac{\partial^3 U}{\partial Y^2 \partial T} - V_0'(1 + \varepsilon A e^{i\omega 0T})\frac{\partial^3 U}{\partial Y^3}\right) \tag{12}$$

$$\frac{\partial V}{\partial T} = -\frac{1}{\rho}\frac{\partial P}{\partial Y} \tag{13}$$

If in Eqn (12), $V'_0 = 0$ and $\phi = 0$, the governing equation of motion is essentially the same as that of the Newtonian fluid.

Also from Eqns (11) and (13), as $\frac{\partial P}{\partial Y}$ is small in the boundary layer, it can be neglected. Hence, the pressure is taken to be constant along any normal and is given by its value outside the boundary layer. If $U'(T)$ is the free-stream velocity, then

$$-\frac{\partial P}{\partial X}=\frac{\partial U'}{\partial T} \tag{14}$$

Then Eqn (12) becomes

$$\rho\left(\frac{\partial U}{\partial T}-V_0'(1+\varepsilon Ae^{i\omega_0 T})\frac{\partial U}{\partial Y}\right)=\frac{\partial U'}{\partial T}+\frac{\phi_1}{2}\frac{\partial^2 U}{\partial Y^2}+\phi_2\left(\frac{\partial^3 U}{\partial Y^2\partial T}-V_0'(1+\varepsilon Ae^{i\omega_0 T})\frac{\partial^3 U}{\partial Y^3}\right) \tag{15}$$

The boundary conditions are U=0 at Y=0 and $U=U'(T)$ as $Y\to\infty$.

Considering periodic free-stream velocity of the form

$$U'(T)=U_o'(1+\varepsilon e^{i\omega_0 T}) \tag{16}$$

and the velocity in the neighbourhood of the plate can be assumed as:

$$U(Y,T)=U_o'[f_1(Y)+\varepsilon e^{i\omega_0 T}f_2(Y)] \tag{17}$$

The following is the scheme of non-dimensionalisation for further analysis

$$U=\frac{\phi_1 u}{\rho L},\quad T=\frac{\rho L^2 t}{\phi_1},\quad P=\frac{\phi_1^2 p}{\rho L^2},\quad V_0'=\frac{\phi_1 v_0'}{\rho L},$$

$$U'=\frac{\phi_1 u'}{\rho L},\ \phi_2=\rho L^2\beta,\ \frac{X}{L}=x,\ \frac{Y}{L}=y,\ U_o'=\frac{\phi_1 u_o'}{\rho L},$$

$$\omega_0=\frac{\phi_1\omega}{\rho L^2},\ V=\frac{\phi_1 v}{\rho L}$$

3. SOLUTION OF THE PROBLEM

The equation of motion in the non dimensional form will now be

$$\left(\frac{\partial u}{\partial t}-v_0'(1+\varepsilon Ae^{i\omega t})\frac{\partial u}{\partial y}\right)=\frac{\partial u'}{\partial t}+\frac{\partial^2 u}{\partial y^2}+\beta\left(\frac{\partial^3 u}{\partial y^2\partial t}-v_0'(1+\varepsilon Ae^{i\omega t})\frac{\partial^3 u}{\partial y^3}\right)$$

where ω is the frequency of the fluctuating stream.

Together with the conditions:

$$u = 0 \text{ at } y = 0 \tag{19}$$

$$\text{and } u = u'(t) \text{ as } Y\to\infty \tag{20}$$

The periodic free-stream velocity Eqn (16) and Eqn (17) in the nondimensional form will be

$$u'(t)=u_o'(1+\varepsilon e^{i\omega t}) \tag{21}$$

and $u(y,t)=u_o'[f_1(y)+\varepsilon e^{i\omega t}f_2(y)]$ (22)

Differentiating Eqn (22) partially wrt t and y, the following set of equations are obtained:

$$\frac{\partial u}{\partial t}=i\omega\varepsilon e^{i\omega t}f_2(y),\ \frac{\partial u}{\partial y}=f_1'(y)+\varepsilon e^{i\omega t}f_2'(y),$$
$$\frac{\partial^2 u}{\partial y^2}=f_1''(y)+\varepsilon e^{i\omega t}f_2''(y),\ \frac{\partial^3 u}{\partial y^3}=f_1'''(y)+\varepsilon e^{i\omega t}f_2'''(y),$$
$$\frac{\partial^3 u}{\partial y^2\partial t}=i\omega\varepsilon e^{i\omega t}f_2''(y),\ \frac{\partial u'}{\partial t}=i\omega\varepsilon e^{i\omega t} \tag{23}$$

Using the above set of equations [Eqn (23)] in Eqn (18) and comparing harmonic terms, viz., constant and $\varepsilon e^{i\omega t}$, while neglecting the coefficients of ε^2, etc, the following set of equations are obtained:

$$\beta f_1'''(y)-f_1''(y)-f_1'(y)=0 \tag{24}$$

$$\beta f_2'''(y)-f_2''(y)(1+i\beta\omega)-f_2'(y)+i\omega f_2(y)=i\omega+Af_1'(y)+A\beta f_1'''(y) \tag{25}$$

where the prime denotes differentiation wrt y.

Using the Eqn (19) in Eqn (22) i.e., $u = 0$ at $y = 0$, one gets

$$0 = u_o'[f_1(0) + \varepsilon e^{i\omega t} f_2(0)]$$

As $u'_0 \neq 0$ and $\varepsilon e^{i\omega t} \neq 0$, $f_1(0) = f_2(0) = 0$

Now using the Eqn (20) in Eqn (22) i.e., $u = u'(t)$ as $y \to \infty$

$$u'(t) = u_o'(1 + \varepsilon e^{i\omega t}) = u_o'[f_1(\infty) + \varepsilon e^{i\omega t} f_2(\infty)]$$

which will yield $f_1(\infty) = f_2(\infty) = 1$

In view of Eqn (22), the boundary conditions from Eqns (19) and (20) will now be

$$f_1(y) = f_2(y) = 0 \text{ at } y = 0 \tag{26}$$

$$f_1(y) = f_2(y) = 1 \text{ at } y = \infty \tag{27}$$

Equations (24) and (25) are of third-order differential equations when $\beta \neq 0$, and for $\beta = 0$ these are reduced to equations governing Newtonian fluid. Hence, it is evident that, the presence of the elastico viscosity of the fluid, increases the order of the governing equations from two to three, and therefore, which requires three boundary conditions for a unique solution. In the present situation, there are only two prescribed boundary conditions as mentioned in Eqns (26) and (27).

To overcome this, following Walters[7] and assuming the solution as

$$\begin{aligned} f_1(y) &= f_{01}(y) + \beta f_{11}(y) + o(\beta^2) \\ f_2(y) &= f_{02}(y) + \beta f_{12}(y) + o(\beta^2) \end{aligned} \tag{28}$$

Differentiating Eqn (28) partially wrt y, the following equations are obtained:

$$\begin{aligned} f_1'(y) &= f_{01}'(y) + \beta f_{11}'(y) + o(\beta^2) \\ f_2'(y) &= f_{02}'(y) + \beta f_{12}'(y) + o(\beta^2) \end{aligned}$$

$$\begin{aligned} f_1''(y) &= f_{01}''(y) + \beta f_{11}''(y) + o(\beta^2) \\ f_2''(y) &= f_{02}''(y) + \beta f_{12}''(y) + o(\beta^2) \end{aligned}$$

$$\begin{aligned} f_1'''(y) &= f_{01}'''(y) + \beta f_{11}'''(y) + o(\beta^2) \\ f_2'''(y) &= f_{02}'''(y) + \beta f_{12}'''(y) + o(\beta^2) \end{aligned} \tag{29}$$

which is valid only for small values of β. Substituting the above set of equations [Eqns (29)] in Eqns (24) and (25), and equating the coefficients of constant term and β. While neglecting the coefficients β^2 onwards, one has the following set of equations:

$$\begin{aligned} & f_{01}''(y) + f_{01}'(y) = 0, \\ & f_{01}'''(y) - f_{11}''(y) - f_{11}'(y) = 0, \\ & f_{02}''(y) + f_{02}'(y) - i\omega f_{02}(y) = -i\omega - A f_{01}'(y), \\ & f_{12}''(y) + f_{12}'(y) - i\omega f_{12}(y) = -i\omega f_{02}''(y) + \\ & \qquad f_{02}'''(y) - A f_{11}'(y) - A f_{01}'''(y), \end{aligned} \tag{30}$$

Using the Eqns (26) and (27) in the Eqn (28), the corresponding boundary conditions are:

$$\begin{aligned} & f_{01}(y) = f_{11}(y) = f_{02}(y) = f_{12}(y) = 0, at, y = 0 \\ & f_{01}(y) = f_{02}(y) = 1, f_{11}(y) = f_{12}(y) = 0, as, y \to \infty \end{aligned} \tag{31}$$

Under the backdrop of Eqn (28), solution of Eqn (30) using the boundary conditions given in Eqn (31) yields:

$$f_1(y) = 1 - e^{-y} - \beta y e^{-y} \tag{32}$$

$$\begin{aligned} f_2(y) = 1 - S e^{-hy} - (1-S)e^{-y} + \beta[(1-S)\{(1+ \\ \frac{i}{\omega})e^{-hy} - ((1+\frac{i}{\omega}) + y)e^{-y}\} - L y e^{-hy}] \end{aligned} \tag{33}$$

where

$$S = 1 - \frac{iA}{\omega}, \quad h = \frac{1}{2}[1 + (1 + i4\omega)^{1/2}]$$

$$L = \frac{Sh^2(h + i\omega)}{(1 + i4\omega)^{1/2}} \tag{34}$$

Hence, the velocity field in the boundary layer is given by

$$\begin{aligned} u(y,t) &= 1 - e^{-y} - \beta y e^{-y} + \varepsilon e^{i\omega t} \\ &\{1 - Se^{-hy} - (1-S)e^{-y} + \beta[(1-S)\{(1+ \\ &\frac{i}{\omega})e^{-hy} - ((1+\frac{i}{\omega}) + y)e^{-y}\} - Lye^{-hy}]\} \end{aligned} \tag{35}$$

Skin friction on the plate is given by

$$\text{Skin-friction} = \frac{\partial u}{\partial y} + \beta\{\frac{\partial^2 u}{\partial y \partial t} - (1 + A\varepsilon e^{i\omega t})\frac{\partial^2 u}{\partial y^2}\}$$

at $y = 0$ (36)

4. RESULTS AND DISCUSSIONS

1. If $\beta = 0$ in the expression for the velocity field given by Eqn (32), the results are in agreement with that of Soundelgekar[2].

2. The effect of elastico-viscosity (β) of the fluid on the velocity profiles were analysed for various values of parameters under consideration. From Figs 1 and 2 it is observed that, there is backflow near the wall for different values of elastico-viscosity (β) and time (t). It is noticed from Fig. 1 that, as the elastico-viscosity of the fluid increases, more of back flow has been seen at the wall while as t increases, the reverse trend is seen in Fig. 2. This effect can be attributed to the fact that the intra molecular forces are much stronger at the entry level than in the core region.

3. Figure 3 shows the effect of suction parameter (A) on the distribution of velocity profile. It is seen that as A increases, the backflow is found to be predominant, which is in agreement with

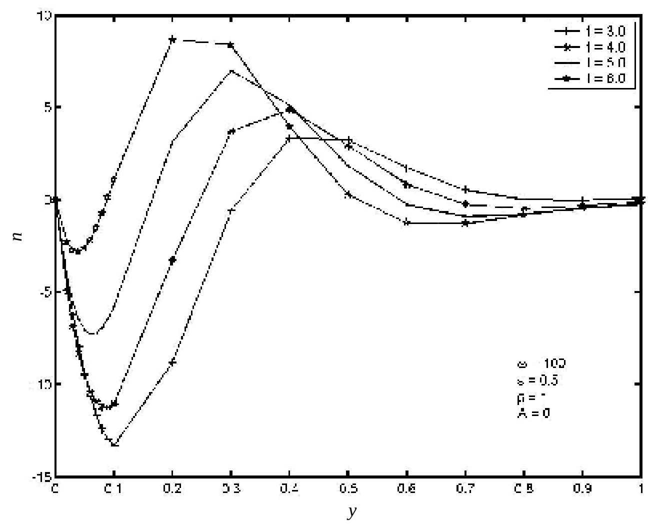

Figure 2. Velocity profiles for different time parameter.

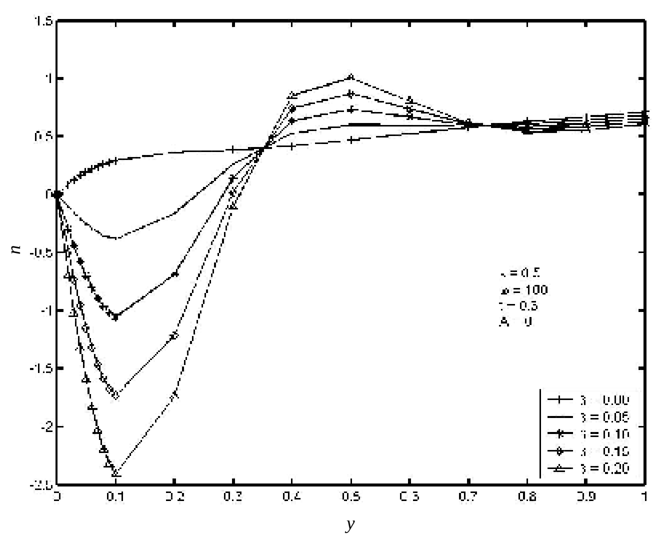

Figure 1. Velocity profiles for different elastico-viscosity parameter.

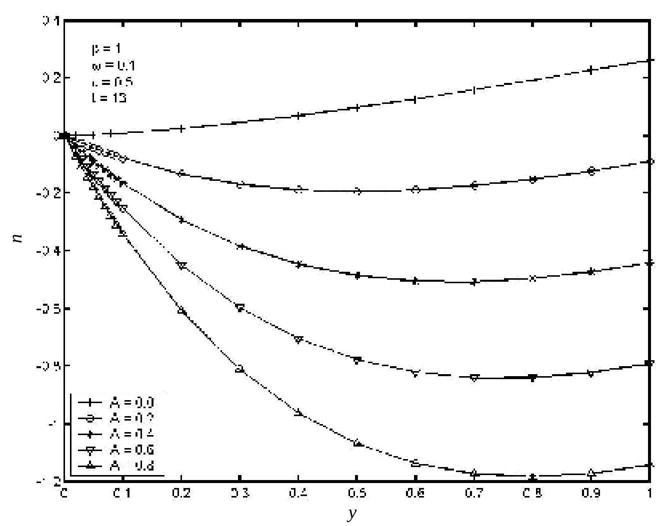

Figure 3. Velocity profiles for different values of suction parameter.

the physical phenomena. This is due to the fact that the recent deformation of the fluid is more predominant than the deformation at the distant past.

4. Figure 4 shows the effect of suction parameter A on the amplitude of the skin friction. As the frequency parameter ω increases, the amplitude of skin friction also increases. Further, as the suction parameter increases, the amplitude of the skin friction decreases.

5. The effect of elastico-viscosity parameter, β on the amplitude of the skin friction has been examined in Fig. 5. It is observed that as the elastico-viscosity parameter decreases, the amplitude of the skin friction also decreases. Further, as the frequency parameter ω increases, the amplitude of the skin friction increases.

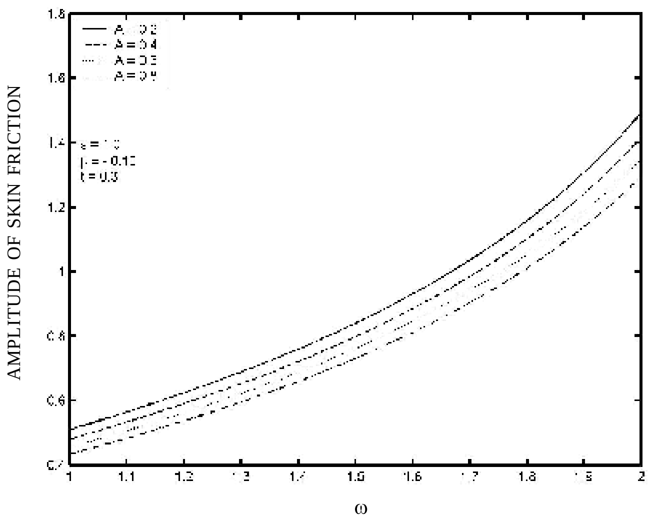

Figure 4. Effect of suction on the amplitude of skin friction.

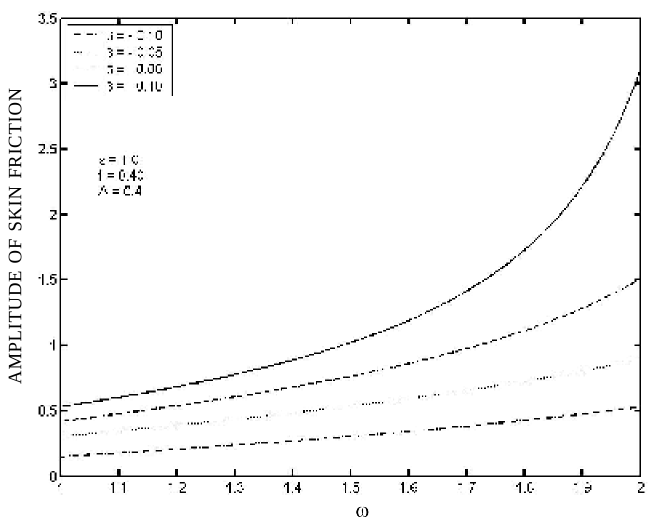

Figure 5. Variation of amplitude of skin friction for different.

5. CONCLUSIONS

Due to the presence of elastico-viscosity parameter, β of the fluid that is under consideration, the backflow occurs at the wall. As β increases, the backflow in the boundary layer region is found to be predominant. This phenomena can be attributed to the material property of recent deformation when compared to the deformation at distant past. However, as one moves away from the plate, the velocity of the fluid is positive for the reason that the material deformation at distant past has almost no effect. In case of the constant suction velocity (A = 0), the velocity of the fluid at the boundary region is affected significantly. This is due to the greater intra-molecular forces at the entry level. Though there is a significant backflow at the wall as t increases, the flow settles down as one moves into the core region. An increase in suction (A) leads to decrease in the amplitude of the skin friction, which is responsible for the increase in the back flow at the wall.

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