ROTATING MHD FLOW OF A GENERALIZED BURGERS' FLUID OVER AN OSCILLATING PLATE EMBEDDED IN A POROUS MEDIUM

by

Ilyas KHAN [a*] ***and Sharidan SHAFIE*** [b]

[a] Department of Basic Sciences, College of Engineering, Majmaah University, Majmaah, Saudi Arabia
[b] Department of Mathematical Sciences, Faculty of Science, University of Technology, Malaysia, Skudai, Johor Bahru, Malaysia

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The present paper is concerned with the magnetohydrodynamic unsteady rotating flows of generalized Burgers' fluid with a porous medium. The flows are created by the plate oscillations. Modified Darcy's law has been employed to model the governing problem. Closed-form solutions corresponding to cosine and sine oscillations are obtained by the Laplace transform method. The performed calculations disclose that Hartmann number, porosity of the medium, angular frequency, and oscillating frequency have strong influence on the velocity. The graphs are presented for such influence and examined carefully.

Key words: *unsteady flows, plate oscillations, generalized Burgers' fluid, rotating system, Laplace transform*

Introduction

Newtonian fluids described by Navier-Stokes equations have been limited in terms of their applications. It is because they cannot precisely describe the characteristics of several physiological fluids such as polymer solutions and molten polymer. In the literature, they are known as non-Newtonian fluids such as ketchup, custard, starch suspension, toothpaste, shampoo, paint, and blood. On the other hand, non-Newtonian fluids have many applications in industries, oil and gas well, drilling, food stuffs, polymer processing, physiology, and cosmetic products. Due to wide diversity of non-Newtonian fluids, several models or constitutive equations have been proposed such as second grade fluid [1, 2], third grade fluid [3], Maxwell fluid [4-6], Oldroyd-B fluid [7], Brinkman type fluids [8] micropolar fluid [9], and nanofluid [10, 11]. Amongst them, there is one which is called the generalized Burgers' fluid. This fluid model is a general form of the Burgers' fluid model which is capable for the description of motion of the Earth's mantle, response of asphalt concrete, geological structures modelling for instance olivine rocks, and the propagation of seismic waves in the interior of the Earth [12].

On the other hand MHD flows in a porous medium have wide applications in the optimization of solidification processes of metals and metal alloys, the geothermal sources investigation and nuclear fuel debris treatment. The flows of viscoelastic fluid in porous medium are prominent in enhanced oil recovery, paper and textile coating and composite manufacturing processes. Further, the MHD viscoelastic fluids in a rotating frame have ample applica-

* Corresponding author; e-mail: ilyaskhanqau@yahoo.com; i.said@mu.edu.sa; sharidan@utm.my

tions in geophysics and astrophysics. Having such motivation in mind, Hayat *et al.* [13, 14] investigated the rotating unsteady MHD flows of a second grade and Maxwell fluids with porous medium analytically using Fourier sine transforms, respectively. Hayat *et al.* [15] also investigated rotating flow of a third grade fluid numerically using Newtons' method followed by Hayat *et al.* [16] where exact solution for rotating flow of a generalized Burgers' fluid are obtained in a porous half space. Jamil and Fetecau [17] studied rotating flows of a generalized Burgers' fluid in cylindrical domains. They obtained exact solutions for velocity field and shear stress between two infinite coaxial cylinders by means of Laplace and finite Hankel transforms. Khan *et al.* [18] studied unsteady MHD rotating flow of an incompressible generalized Burgers' fluid past a suddenly moved plate through a porous medium. Few other attempts on rotating flow are given in [19-21].

Based on the above motivations, the present study aims to investigate the oscillatory and rotating flows in a generalized Burgers' fluid. The fluid is magnetohydrodynamic in the presence of an applied magnetic field. The fluid occupying a half porous space is bounded by a rigid and non-conducting plate. Exact solutions are obtained using the Laplace transform technique [22]. Graphs are shown for the description of various parameters of interest.

Definition of the problem

We consider the flow of generalized Burgers' fluid filling a semi-infinite porous space $z>0$ and rigid plate at $z = 0$. We select z-axis in a normal direction to the plate and the whole system (both fluid and plate) are in a state of solid body rotation with constant angular velocity $\mathbf{\Omega} = \Omega \vec{\mathrm{k}}$ ($\vec{\mathrm{k}}$ is a unit vector in the z-direction). The fluid is electrically conducting under an applied magnetic field (0, 0, B_0), and the induced magnetic field is not incorporated for small magnetic Reynolds number. Initially, the whole system is at rest and for $t>0$, the flow is induced by the plate oscillations in its own plane. The governing flow equation with imposed initial and boundary conditions in dimensionless form are given by [16]:

$$\frac{\partial^3 G(\xi,\tau)}{\partial t^3} + (b + aC + dB)\frac{\partial^2 G(\xi,\tau)}{\partial t^2} + (1 + bC + \gamma B)\frac{\partial G(\xi,\tau)}{\partial t} + (C + B)G(\xi,\tau) =$$

$$= \left(1 + \gamma\frac{\partial}{\partial \tau} + d\frac{\partial^2}{\partial \tau^2}\right)\frac{\partial^2 G(\xi,\tau)}{\partial \xi^2}, \quad \xi,\ \tau > 0 \tag{1}$$

$$G(0,\tau) = H(\tau)\cos(\omega\tau), \quad G(0,\tau) = \sin(\omega\tau), \quad \tau > 0 \tag{2}$$

$$G(\xi,\tau) \to 0 \quad \text{as} \quad \xi \to \infty,\ \tau > 0 \tag{3}$$

$$G(\xi,0) = \frac{\partial G(\xi,0)}{\partial \tau} = \frac{\partial^2 G(\xi,0)}{\partial \tau^2} = 0, \quad \xi > 0 \tag{4}$$

where

$$\xi = \frac{zU_0}{\nu}, \quad G = \frac{F}{U_0}, \quad \tau = \frac{tU_0^2}{\nu}, \quad W = \frac{\Omega\nu}{U_0^2}, \quad a = \frac{\lambda_2 U_0^4}{\nu^2}, \quad b = \frac{\lambda_1 U_0^2}{\nu}, \quad d = \frac{\lambda_4 U_0^4}{\nu^2}, \quad \gamma = \frac{\lambda_3 U_0^2}{\nu},$$

$$\mathrm{M}^2 = \frac{\delta B_0^2 \nu}{\rho U_0^2}, \quad \frac{1}{K} = \frac{\varphi \nu^2}{kU_0^2}, \quad C = 2iW + \mathrm{M}^2, \quad \omega = \frac{\omega_0 \nu}{U_0^2} \tag{5a-l}$$

with $F = u + iv$. With help of the solution of eqs. (1)-(4), we write:

$$\overline{G}_c(\xi,q)=\frac{q}{q^2+\omega^2}\exp\left[-\sqrt{\frac{aq^3+a_0q^2+b_0q+c_0}{dq^2+\gamma q+1}}\xi\right] \tag{6}$$

$$\overline{G}_s(\xi,q)=\frac{w}{q^2+\omega^2}\exp\left[-\sqrt{\frac{aq^3+a_0q^2+b_0q+c_0}{dq^2+\gamma q+1}}\xi\right] \tag{7}$$

where q is a Laplace transform parameter and:

$$a_0=b+aC+dB,\quad b_0=1+bC+\gamma B,\quad c_0=C+B \tag{8}$$

We now write eqs. (6) and (7) as:

$$\overline{G}_c(\xi,q)=\overline{G}_1(q)\overline{G}_3(\xi,q),\quad \overline{G}_s(\xi,q)=\overline{G}_2(q)\overline{G}_3(\xi,q) \tag{9a,b}$$

where

$$\overline{G}_1(q)=q/(q^2+\omega^2),\ \overline{G}_2(q)=w/(q^2+\omega^2),\ \overline{G}_3(\xi,q)=\exp\left[-\sqrt{w(q)}\xi\right]$$
$$w(q)=\frac{aq^3+a_0q^2+b_0q+c_0}{dq^2+\gamma q+1} \tag{10a,b,c,d}$$

Hence, we obtain:

$$G_c(\xi,\tau)=(G_1\otimes G_3)(\tau)=\int_0^\tau G_1(\tau-z)G_3(\xi,z)\,\mathrm{d}z$$
$$G_s(\xi,\tau)=(G_2\otimes G_3)(\tau)=\int_0^\tau G_2(\tau-z)G_3(\xi,z)\,\mathrm{d}z \tag{11a,b}$$

Equations (10a,b) can be transferred into:

$$G_1(\tau)=H(\tau)\cos(\omega\tau),\quad G_2(\tau)=\sin(\omega\tau) \tag{12a,b}$$

Using the inversion formula for compound functions, we obtain:

$$\pounds^{-1}\{F[w(q)]\}=\pounds^{-1}\{F(q)\}=\int_0^\infty f(u)\,g(u,\tau)\,\mathrm{d}u \tag{12a,b}$$

where $f(\tau)=\pounds^{-1}\{F(q)\}$, and $g(u,\tau)=\pounds^{-1}\{\mathrm{e}^{-uw(q)}\}$.
Choosing $f(\xi,q)=\mathrm{e}^{-\xi\sqrt{q}}$, we have that:

$$f(\xi,\tau)=\pounds^{-1}(\mathrm{e}^{-\xi\sqrt{q}})=\frac{\xi}{2\tau\sqrt{\pi\tau}}\exp\left(\frac{-\xi^2}{4\tau}\right),\quad \xi>0$$
$$G_3(\xi,\tau)=\pounds^{-1}[\overline{G}_3(\xi,q)]=\frac{\xi}{2\sqrt{\pi}}\int_0^\infty\frac{1}{u\sqrt{u}}\exp\left(\frac{-\xi^2}{4u}\right)g(u,\tau)\,\mathrm{d}u \tag{13a,b}$$

where

$$g(u,\tau)=\pounds^{-1}[\mathrm{e}^{-uw(q)}]=\mathrm{e}^{-u\eta_0}\,\pounds^{-1}\left\{\exp\left(-\frac{ua}{d}q\right)[1-H_1(q)-H_2(q)+H_1(q)H_2(q)]\right\}$$

$$\eta_0=\frac{a_0}{d}-\frac{a\gamma}{d^2},\quad \eta_1=\frac{A_1q_1+A_2}{\sqrt{\gamma^2-4d}},\quad \eta_2=\frac{A_1q_2+A_2}{\sqrt{\gamma^2-4d}},$$

$$A_1=b_0-\frac{a}{d}-\frac{a_0\gamma}{d}+\frac{a\gamma^2}{d^2},\quad A_2=c_0-\frac{a_0}{d}+\frac{a\gamma}{d^2}$$

with

$$H_1(q)=1-\exp\left(-\frac{u\eta_1}{q-q_1}\right),\quad H_2(q)=1-\exp\left(-\frac{u\eta_2}{q-q_2}\right) \tag{14a,b}$$

From eqs. (14a,b), we write:

$$\begin{aligned}h_1(\tau)&=£^{-1}\{H_1(q)\}=\sqrt{\frac{\eta_1u}{\tau}}\mathrm{e}^{q_1\tau}J_1(2\sqrt{\eta_1u\tau}),\\ h_2(\tau)&=£^{-1}\{H_2(q)\}=\sqrt{\frac{\eta_2u}{\tau}}\mathrm{e}^{q_2\tau}J_1(2\sqrt{\eta_2u\tau})\end{aligned} \tag{15a,b}$$

where $J_1(\cdot)$ denotes the Bessel function of first kind of order one.

Then, finally one has:

$$g(u,\tau)=\mathrm{e}^{-\eta_0u}\left[\begin{array}{c}\delta\left(\tau-\frac{au}{d}\right)-\sqrt{\eta_1u}\int\limits_0^\tau\frac{\delta\left(s-\frac{au}{d}\right)}{\sqrt{\tau-s}}\mathrm{e}^{q_1(\tau-s)}J_1[2\sqrt{\eta_1u(\tau-s)}]\mathrm{d}s-\\ -\sqrt{\eta_2u}\int\limits_0^\tau\frac{\delta\left(s-\frac{au}{d}\right)}{\sqrt{\tau-s}}\mathrm{e}^{q_2(\tau-s)}J_1[2\sqrt{\eta_2u(\tau-s)}]\mathrm{d}s+\\ +u\sqrt{\eta_1\eta_2}\int\limits_0^\tau\int\limits_0^s\frac{\delta\left(\tau-s-\frac{au}{d}\right)}{\sqrt{\delta(s-\delta)}}\mathrm{e}^{q_1\sigma+q_2(s-\sigma)}J_1(2\sqrt{\eta_1u\sigma})J_1[2\sqrt{\eta_2u(s-\sigma)}]\mathrm{d}s\,\mathrm{d}\sigma\end{array}\right] \tag{16}$$

Insertion of eq. (16) into eq. (13b) leads to the result:

$$\begin{aligned}G_3(\xi,\tau)&=\frac{\xi}{2\sqrt{\pi}}\int\limits_0^\infty\frac{\delta\left(\tau-\frac{au}{d}\right)}{u\sqrt{u}}\exp\left(\frac{-\xi^2}{4u}-\eta_0u\right)\mathrm{d}u-\\ &-\frac{\sqrt{\eta_1}\xi}{2\sqrt{\pi}}\int\limits_0^\tau\int\limits_0^\infty\frac{1}{u}\frac{\delta\left(s-\frac{au}{d}\right)}{\sqrt{\tau-s}}\exp\left[\frac{-\xi^2}{4u}+q_1(\tau-s)-\eta_0u\right]J_1[2\sqrt{\eta_1u(\tau-s)}]\mathrm{d}u\ \mathrm{d}s-\\ &-\frac{\sqrt{\eta_2}\xi}{2\sqrt{\pi}}\int\limits_0^\tau\int\limits_0^\infty\frac{1}{u}\frac{\delta\left(s-\frac{au}{d}\right)}{\sqrt{(\tau-s)}}\exp\left[\frac{-\xi^2}{4u}+q_2(\tau-s)-\eta_0u\right]J_1[2\sqrt{\eta_2u(\tau-s)}]\mathrm{d}u\ \mathrm{d}s+\\ &+\frac{\sqrt{\eta_1\eta_2}\xi}{2\sqrt{\pi}}\int\limits_0^\tau\int\limits_0^s\int\limits_0^\infty\frac{\delta\left(\tau-s-\frac{au}{d}\right)}{\sqrt{u\sigma(s-\sigma)}}\exp\left[\frac{-\xi^2}{4u}+q_1\sigma+q_2(s-\sigma)-\eta_0u\right]\\ &J_1(2\sqrt{\eta_1u\sigma})J_1[2\sqrt{\eta_2u(s-\sigma)}]\mathrm{d}u\ \mathrm{d}s\ \mathrm{d}\sigma\end{aligned} \tag{17}$$

Taking eqs. (12a,b) and (17) into consideration, from eq. (11a,b) we have:

$$G_c(\xi,\tau)=H(\tau)\left\{\frac{\xi\sqrt{a}}{2\sqrt{\pi d}}\int_0^\tau\frac{\cos\omega(\tau-z)}{z\sqrt{z}}\exp\left(\frac{-a\xi^2}{4dz}-\frac{d\eta_0}{a}z\right)\mathrm{d}z-\right.$$

$$-\frac{\sqrt{\eta_1}\xi}{2\sqrt{\pi}}\int_0^\tau\int_0^z\frac{\cos\omega(\tau-z)}{s\sqrt{z-s}}\exp\left[\frac{-a\xi^2}{4ds}+q_1(z-s)-\frac{\eta_0 d}{a}s\right]J_1\left[2\sqrt{\frac{\eta_1 d}{a}s(z-s)}\right]\mathrm{d}s\,\mathrm{d}z-$$

$$-\frac{\sqrt{\eta_2}\xi}{2\sqrt{\pi}}\int_0^\tau\int_0^z\frac{\cos\omega(\tau-z)}{\sqrt{s(z-s)}}\exp\left[\frac{-a\xi^2}{4ds}+q_2(z-s)-\frac{\eta_0 d}{a}s\right]J_1\left[2\sqrt{\frac{\eta_2 d}{a}s(z-s)}\right]\mathrm{d}s\,\mathrm{d}z+$$

$$+\frac{\sqrt{\eta_1\eta_2 d}\,\xi}{2\sqrt{a\pi}}\int_0^\tau\int_0^z\int_0^s\frac{\cos\omega(\tau-z)}{\sqrt{\sigma(s-\sigma)(z-s)}}\exp\left[\frac{-a\xi^2}{4d(z-s)}+q_1\sigma+q_2\left(s-\sigma\right)-\frac{\eta_0 d}{a}(z-s)\right]$$

$$\left.J_1\left[2\sqrt{\frac{\eta_1 d}{a}\sigma(z-s)}\right]J_1\left[2\sqrt{\frac{\eta_2 d}{a}(z-s)(s-\sigma)}\right]\mathrm{d}s\,\mathrm{d}\sigma\,\mathrm{d}z\right\} \tag{18}$$

$$G_s(\xi,\tau)=\frac{\xi\sqrt{a}}{2\sqrt{\pi d}}\int_0^\tau\frac{\sin\omega(\tau-z)}{z\sqrt{z}}\exp\left(\frac{-a\xi^2}{4dz}-\frac{\eta_0 d}{a}z\right)\mathrm{d}z-$$

$$-\frac{\sqrt{\eta_1}\xi}{2\sqrt{\pi}}\int_0^\tau\int_0^z\frac{\sin\omega(\tau-z)}{s\sqrt{z-s}}\exp\left[\frac{-a\xi^2}{4ds}+q_1(z-s)-\frac{\eta_0 d}{a}s\right]J_1\left[2\sqrt{\frac{\eta_1 d}{a}s(z-s)}\right]\mathrm{d}s\,\mathrm{d}z-$$

$$-\frac{\sqrt{\eta_2}\xi}{2\sqrt{\pi}}\int_0^\tau\int_0^z\frac{\sin\omega(\tau-z)}{\sqrt{s\left(z-s\right)}}\exp\left[\frac{-a\xi^2}{4ds}+q_2(z-s)-\frac{\eta_0 d}{a}s\right]J_1\left[2\sqrt{\frac{\eta_2 d}{a}s(z-s)}\right]\mathrm{d}s\,\mathrm{d}z+$$

$$+\frac{\sqrt{\eta_1\eta_2 d}\,\xi}{2\sqrt{a\pi}}\int_0^\tau\int_0^z\int_0^s\frac{\sin\omega(\tau-z)}{\sqrt{\sigma(s-\sigma)(z-s)}}\exp\left[\frac{-a\xi^2}{4d(z-s)}+q_1\sigma+q_2(s-\sigma)-\frac{\eta_0 d}{a}(z-s)\right]$$

$$J_1\left[2\sqrt{\frac{\eta_1 d}{a}\sigma(z-s)}\right]J_1\left[2\sqrt{\frac{\eta_2 d}{a}(s-\sigma)(z-s)}\right]\mathrm{d}s\,\mathrm{d}\sigma\,\mathrm{d}z \tag{19}$$

Making use of eq. (19), for $\omega\to 0$ we give:

$$G_c(\xi,\tau)=\left[\frac{\xi\sqrt{a}}{2\sqrt{\pi d}}\int_0^\tau\frac{1}{z\sqrt{z}}\exp\left(\frac{-a\xi^2}{4dz}-\frac{\eta_0 d}{a}z\right)\mathrm{d}z-\right.$$

$$-\frac{\sqrt{\eta_1}\xi}{2\sqrt{\pi}}\int_0^\tau\int_0^z\frac{1}{s\sqrt{z-s}}\exp\left[\frac{-a\xi^2}{4ds}+q_1(z-s)-\frac{\eta_0 d}{a}s\right]J_1\left(2\sqrt{\frac{\eta_1 d}{a}s(z-s)}\right)\mathrm{d}s\,\mathrm{d}z-$$

$$-\frac{\sqrt{\eta_2}\xi}{2\sqrt{\pi}}\int_0^\tau\int_0^z \frac{1}{\sqrt{s(z-s)}}\exp\left[\frac{-a\xi^2}{4ds}+q_2(z-s)-\frac{\eta_0 d}{a}s\right]J_1\left[2\sqrt{\frac{\eta_2 d}{a}s(z-s)}\right]\mathrm{d}s\,\mathrm{d}z+$$

$$+\frac{\sqrt{\eta_1\eta_2 d}\,\xi}{2\sqrt{a\pi}}\int_0^\tau\int_0^z\int_0^s \frac{1}{\sqrt{\sigma(s-\sigma)(z-s)}}\exp\left[\frac{-a\xi^2}{4d(z-s)}+q_1\sigma+q_2(s-\sigma)-\frac{\eta_0 d}{a}(z-s)\right]$$

$$J_1\left[2\sqrt{\frac{\eta_1 d}{a}\sigma(z-s)}\right]J_1\left[2\sqrt{\frac{\eta_2 d}{a}(s-\sigma)(z-s)}\right]\mathrm{d}s\,\mathrm{d}\sigma\,\mathrm{d}z\Bigg] \tag{20}$$

which corresponds to the Stokes' first problem for MHD generalized Burgers' fluid in a porous medium and rotating frame.

Results and discussions

In the present work, the results due to cosine oscillation of plate have been included only. However, it is noticed that sine oscillation of plate yields results which are qualitatively similar to that of cosine oscillation. The variation of Hartmann number M with the parameters $W = \omega = 0.5$, $K = 1$, $b = 0.02$, $a = 0.04$, $\gamma = 0.08$, and $d = 0.009$ has been shown in fig. 1. It is found that both real and imaginary parts of velocity decrease when M increases. In fact, this is because of an applied magnetic field, which generates a resistive force, which is just like a drag force. Such force offers resistance to the flow and consequently the velocity decreases. Figure 2 has been prepared for the influence of parameter K on the velocity with the parameters M = 5, $W = a = 0.5$, $\omega = 4$, $b = 0.5$, $\gamma = 0.8$, and $d = 6$. It is noted that M and K have opposite role on the velocity. In other words, increase in K leads to a decrease in the drag force,

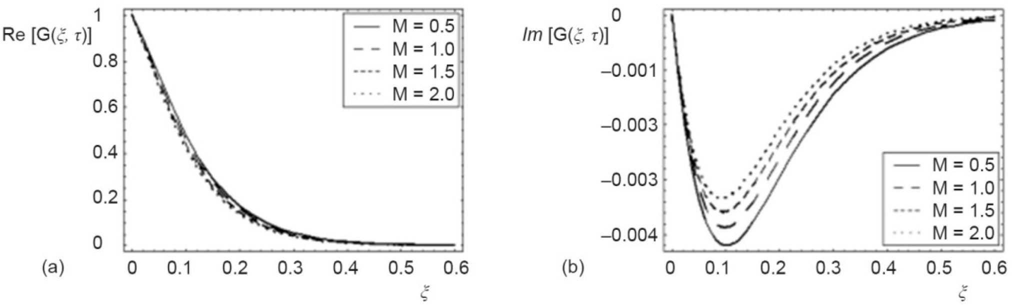

Figure 1. Variation of M on the velocity profiles

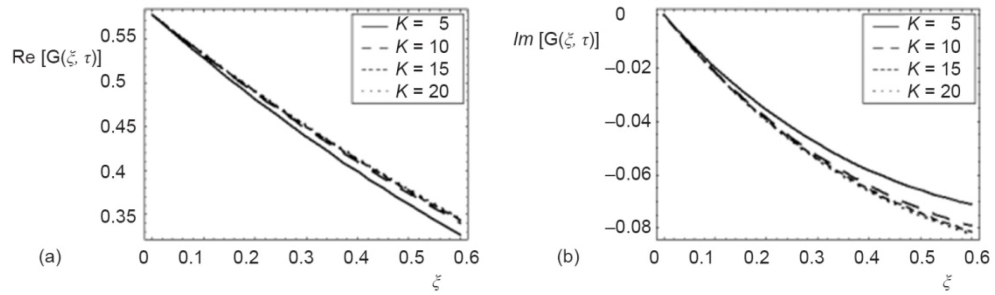

Figure 2. Variation of *K* on the velocity profiles

which ultimately increases the velocity. Figure 3 has been plotted in order to illustrate the behavior of W on the velocity with the parameters M = a = 0.5, ω = 5, K = 2, b = 1, γ = 0.8, and d = 0.009. It is noted that on increasing W, the magnitude of real part of velocity and boundary layer thickness decrease whereas the effect of W on imaginary part of the velocity is quite opposite to that of the real part of the velocity. The magnitude of velocity and boundary layer thickness increase by increasing W. The variation of ω and W on the velocity with the parameters M = b = 0.5, W = 1.5, K = 2, a = d = 1, and γ = 0.8 are similar in a qualitative sense as shown in fig. 4.

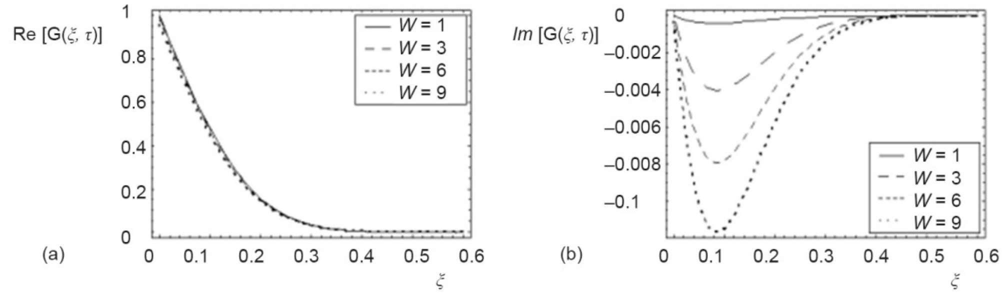

Figure 3. Variation of W on the velocity profiles

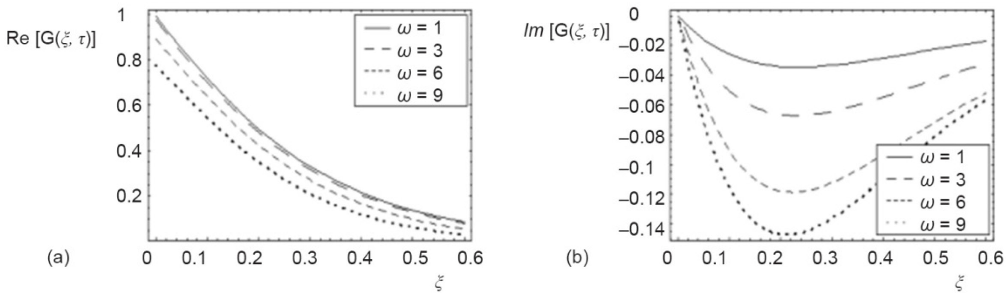

Figure 4. Variation of ω on the velocity profiles

Conclusions

Exact solutions for the unsteady MHD flow of a generalized Burgers' fluid in a porous medium and rotating frame are obtained by Laplace transform method. Results of velocity for cosine oscillations of the plate are plotted graphically and discussed. It is found that velocity decreases with increasing magnetic parameter while increases for large values of permeability parameter. Moreover, the effects of rotating and oscillating frequency parameters are opposite.

Nomenclature

B_0 – applied magnetic field, [T]
F – complex velocity, [ms^{-1}]
$H(t)$ – Heaviside function, [–]
$J_1(\cdot)$ – Bessel function, [–]
M – Hartmann number , [–]
U_0 – reference velocity, [ms^{-2}]
W – dimensionless rotation parameter, [–]
Z – space variable, [m]

Greek symbols

$\delta(\cdot)$ – Dirac delta function, [–]
η – dimensionless space variable, [–]
λ_1, λ_2 – retardation time, [s]
λ_3, λ_4 – material constant, [–]
ρ – fluid density, [kgm^{-3}]
Ω – angular velocity, [$rads^{-1}$]
ω_0 – oscillating frequency, [s^{-1}]

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