

PERMANENT SOLUTIONS FOR MHD MODIFIED STOKES PROBLEMS OF SOME MAXWELL FLUIDS WITH POWER-LAW DEPENDENCE OF VISCOSITY ON PRESSURE*

Constantin Fetecau[†]

Dedicated to the memory of Professor Mihail Megan

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Abstract

Modified Stokes problems for a class of electrically conducting upper-convected incompressible Maxwell fluids with pressure-dependent viscosity are analytically investigated when the influence of magnetic field and gravitational acceleration is taken in consideration. Simple analytic expressions are provided for the dimensionless permanent velocity and shear stress fields. They satisfy the governing equations and boundary conditions and reduce to known results from the existing literature in limiting cases. The influence of physical parameters on the fluid behavior is graphically underlined and discussed. Fluids with pressure-dependent viscosity flow faster than ordinary fluids and their velocity declines in the presence of magnetic field. Permanent shear stress for the modified first problem of Stokes is constant on whole flow domain although the corresponding velocity is function of spatial variable.

Keywords: MHD modified Stokes problems, Maxwell fluids, pressure-dependent viscosity.

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[†]c.fetecau@yahoo.com, Academy of Romanian Scientists, 3 Ilfov, Bucharest 050044, Romania

1 Introduction

Generally, in the existing literature, the fluid viscosity is considered to be constant. However, the experimentalists clearly showed that it varies with pressure. There is a large amount of works regarding this problem. For the literature prior to 1931 the book of Bridgman [5] is welcome. Other experimental studies that confirm the dependence of viscosity on pressure have been developed, for instance, by Griest et al. [11], Johnson and Cameron [16], Johnson and Tevaarwerk [17] and Bair and Winer [3]. Some experimental investigations were done by Iqbal and Hasan [15] for glycerin and Bair and Kottke [2] for isopropanol and lubricants. An important domain where the influence of pressure on viscosity cannot be ignored is the elastohydrodynamic lubrication [25] where the fluid viscosity strongly varies with pressure. A comprehensive review concerning this problem can be found in the works of Binding et al. [4] and Goubert et al. [10]. However, does not exist a pressure-viscosity law that holds for all types of fluids. At low and high pressures, for instance, the linear and exponential laws are adequate to describe the experimental data [13]. Here, we shall consider a power-law dependence of viscosity on pressure and the gravitation effect will be taken in consideration.

In the same time, the obtaining of exact solutions is very important to develop a research domain with multiple applications in lubrication, micro fluidics and geophysics, crude oil and fuel oil pumping, polymer and food processing and pharmaceutical manufacturing (see for instance Hamrock et al. [12] and Martinez-Boza et al. [19]). First exact steady solutions for motions of Newtonian fluids with pressure-dependent viscosity in which the gravitation is taken into account seem to be those of Rajagopal [21, 22]. Velocity fields for other steady motions of same fluids in rectangular ducts were also determined by Akyildiz and Siginer [1] and Housiadas and Giorgioui [14]. Exact solutions for the modified Stokes' problems were provided by Rajagopal et al. [23], Prusa [20] and Fetecau and Agop [7]. A part of these results have been extended to Maxwell fluids with pressure-dependent viscosity by Fetecau et al. [9] and Fetecau and Rauf [8]. The influence of magnetic field on modified Stokes problems for Maxwell fluids with exponential dependence of viscosity on pressure has been recently investigated by Fetecau [6]. Interaction between a moving fluid and magnetic field has multiple applications in physics, chemistry and engineering.

In the present work we establish simple exact expressions for the dimensionless velocity and shear stress fields corresponding to the modified Stokes' problems for incompressible Maxwell fluids with power-law depen-

dence of viscosity on pressure of index two. The effects of magnetic field and gravitational acceleration are taken into consideration. The correctness of results that have been obtained is graphically proved comparing with known results from the literature. Graphical representations are used to show the oscillatory demeanor of the fluid motion in the case the second problem of Stokes and the influence of physical parameters on the fluid velocity in the case of the first problem of Stokes. They show that the fluids with pressure-dependent viscosity flow faster in comparison with the ordinary fluids and the fluid velocity declines in the presence of a magnetic field.

2 Constitutive and governing equations

Constitutive equations of the upper-convected incompressible Maxwell fluids with pressure-dependent viscosity are given by the relations [18]

$$T = -pI + S, \quad S + \lambda \frac{DS}{Dt} = \eta(p)(L + L^T), \quad (1)$$

where T and S are stress and extra-stress tensors, respectively, I is the unit tensor, L is the gradient of the velocity vector w , p is the Laplace multiplier, λ is the relaxation time, D/Dt denotes the time upper-convected derivative and $\eta(p)$ is the fluid viscosity. For simplicity, like Karra et al. [18], we shall refer to p as pressure. In the following we shall consider the case when

$$\eta(p) = \mu[\alpha(p - p_0) + 1]^2. \quad (2)$$

Here, μ is the fluid viscosity at the reference pressure p_0 and $\alpha > 0$ is the dimensional pressure-viscosity coefficient. If $\alpha = 0$, the equations (1) define ordinary upper-convected incompressible Maxwell fluids. If $\lambda = 0$, these equations correspond to the incompressible Newtonian fluids with pressure-dependent viscosity.

Let us assume that an electrically conducting upper-convected incompressible Maxwell fluid (ECUCIMF) with pressure-dependent viscosity, whose constitutive equations are given by the relations (1) and (2), is stationary between two infinite horizontal parallel flat plates. After the initial moment $t = 0$ the lower plate begins to oscillate along its plane with the velocity $W \cos(\omega t)$ or $W \sin(\omega t)$ and a magnetic field of constant strength B acts orthogonal to plates. Here, ω is the oscillations frequency and W is a constant velocity. The resulting motions correspond to the magneto-hydrodynamic (MHD) modified Stokes second problem. Following Rajagopal [21], we are looking for a velocity vector w and a pressure p of the form

$$w = w(z, t) = w(z, t)e_y, \quad p = p(z), \quad (3)$$

reported to a fixed Cartesian coordinate system x, y and z in which e_y is the unit vector along the y -axis. By substituting the velocity vector $w(z, t)$ from Eq. (3) in the second relation (1) and assuming that the extra-stress tensor S , like the velocity vector w is also a function of z and t , it results that its non-null component $\tau(z, t) = S_{yz}(z, t)$ satisfies the governing equation

$$\left(1 + \lambda \frac{\partial}{\partial t}\right) \tau(z, t) = \mu[\alpha(p - p_0) + 1]^2 \frac{\partial w(z, t)}{\partial z}; \quad 0 < z < d, \quad t > 0, \quad (4)$$

where d is the distance between the two plates.

In the following we assume that the fluid, whose magnetic permeability is constant, is finitely conducting. In addition, the induced magnetic field is negligible in comparison with the applied magnetic field and there is no surplus electric charge distribution inside. In these conditions the balance of linear momentum reduces to the relevant relations [24]

$$\rho \frac{\partial w(z, t)}{\partial t} = \frac{\partial \tau(z, t)}{\partial z} - \sigma B^2 w(z, t), \quad \frac{dp(z)}{dz} + \rho g = 0; \quad 0 < z < d, \quad t > 0. \quad (5)$$

In these relations ρ is the fluid density, σ is electrical conductivity and g is the gravitational acceleration. From the second relation (5) it results that

$$p(z) = \rho g(d - z) + p_0 \quad \text{where } p_0 = p(d). \quad (6)$$

The fluid pressure at the lower plate is $p(0) = p_0 + \rho g d$. The two unknown functions $w(z, t)$ and $\tau(z, t)$ have to satisfy the next initial and boundary conditions:

$$w(z, 0) = 0, \quad \tau(z, 0) = 0; \quad 0 \leq z \leq d, \quad (7)$$

$$w(0, t) = W \cos(\omega t) \quad \text{or} \quad W \sin(\omega t), \quad w(d, t) = 0; \quad t > 0. \quad (8)$$

Introducing the next non-dimensional variables, functions and parameters

$$z^* = \frac{1}{d} z, \quad t^* = \frac{\nu}{d^2} t, \quad w^* = \frac{1}{W} w, \quad \tau^* = \frac{d}{\mu W} \tau, \quad \alpha^* = \alpha \rho g d, \quad \omega^* = \frac{d^2}{\nu} \omega, \quad (9)$$

and renouncing to the star notation, one finds dimensionless forms of the governing equations

$$\left(1 + We \frac{\partial}{\partial t}\right) \tau(z, t) = [\alpha(1 - z) + 1]^2 \frac{\partial w(z, t)}{\partial z}; \quad 0 < z < 1, \quad t > 0, \quad (10)$$

$$\frac{\partial w(z, t)}{\partial t} = \frac{\partial \tau(z, t)}{\partial z} - M w(z, t); \quad 0 < z < 1, \quad t > 0. \quad (11)$$

The Weissenberg number We and the magnetic parameter M are defined by the relations

$$We = \frac{\nu\lambda}{d^2}, \quad M = \frac{\sigma B^2}{\mu} d^2, \quad (12)$$

while the corresponding initial and boundary conditions are

$$w(z, 0) = \tau(z, 0) = 0; \quad 0 \leq z \leq 1, \quad (13)$$

$$w(0, t) = \cos(\omega t) \quad \text{or} \quad \sin(\omega t), \quad w(1, t) = 0; \quad t > 0. \quad (14)$$

Since the two motions induced by cosine or sine oscillations of the lower plate become steady or permanent in time, an important problem for the experimental researchers is to know the time to reach this state. In order to determine this time it is sufficient to know the permanent (long time or steady state) solutions $w_{cp}(z, t)$, $\tau_{cp}(z, t)$, or $w_{sp}(z, t)$, $\tau_{sp}(z, t)$ of the system of partial differential equations (10, (11) with the boundary conditions (14). These solutions are independent of the initial conditions (13). Once these solutions are determined, as usual, the time required to reach steady state can be graphically obtained. It is the time after which the diagrams of the starting solutions $w_c(z, t)$, $\tau_c(z, t)$ or $w_s(z, t)$, $\tau_s(z, t)$ (numerical solutions) overlap those of the corresponding permanent solutions. This is the reason that, in the following section, we shall provide exact expressions for the permanent solutions only.

3 Analytic expressions for the permanent solutions

3.1 Modified Stokes second problem

In order to determine exact solutions for the system of partial differential equations (10), (11) with the boundary conditions (14) we shall use the complex velocity and shear stress fields

$$\begin{aligned} w_{com}(z, t) &= w_{cp}(z, t) + iw_{sp}(z, t), \\ \tau_{com}(z, t) &= \tau_{cp}(z, t) + i\tau_{sp}(z, t); \quad 0 < z < 1, \quad t \in R, \end{aligned} \quad (15)$$

where i is the imaginary unit. The two dimensionless complex entities $w_{com}(z, t)$ and $\tau_{com}(z, t)$ have to satisfy the governing equations

$$\begin{aligned} \left(1 + We \frac{\partial}{\partial t}\right) \frac{\partial w_{com}(z, t)}{\partial t} &= [\alpha(1 - z) + 1]^2 \frac{\partial^2 w_{com}(z, t)}{\partial z^2} \\ -2\alpha[\alpha(1 - z) + 1] \frac{\partial w_{com}(z, t)}{\partial z} &- M \left(1 + We \frac{\partial}{\partial t}\right) w_{com}(z, t); \end{aligned} \quad (16)$$

$$0 < z < 1, \quad t \in R,$$

$$\begin{aligned} \left(1 + We \frac{\partial}{\partial t}\right) \tau_{com}(z, t) &= [\alpha(1 - z) + 1]^2 \frac{\partial w_{com}(z, t)}{\partial t}; \end{aligned} \quad (17)$$

$$0 < z < 1, \quad t \in R,$$

with the boundary conditions

$$w_{com}(0, t) = e^{i\omega t}, \quad w_{com}(1, t) = 0; \quad t \in R. \quad (18)$$

Equation (16) has been obtained eliminating $\tau(z, t)$ between Eqs. (10) and (11).

Making the change of the independent variable

$$z = (1 + \alpha - e^r)/\alpha, \quad (19)$$

the equation (16) reduces to a partial differential equation with constant coefficients, namely

$$\begin{aligned} \left(1 + We \frac{\partial}{\partial t}\right) \frac{\partial w_{com}(r, t)}{\partial t} &+ M \left(1 + We \frac{\partial}{\partial t}\right) w_{com}(r, t) \\ &= \alpha^2 \left[\frac{\partial^2 w_{com}(r, t)}{\partial r^2} + \frac{\partial w_{com}(r, t)}{\partial r} \right]; \end{aligned} \quad (20)$$

$$0 < r < a, \quad t \in R.$$

The corresponding boundary conditions are

$$w_{com}(0, t) = 0, \quad w_{com}(a, t) = e^{i\omega t}; \quad t \in R, \quad (21)$$

where $a = \ln(1 + \alpha)$.

The linearity of the partial differential equation (20) and the form of boundary conditions (21) suggest us to look for a solution of the form

$$w_{com}(r, t) = U(r)e^{i\omega t}; \quad 0 < r < a, \quad t \in R. \quad (22)$$

The complex function $U(\cdot)$ that has to be solution of the boundary value problem

$$\frac{d^2U(r)}{dr^2} + \frac{dU(r)}{dr} = \frac{\beta}{\alpha^2} U(r); \quad U(0) = 0, \quad U(1) = 1, \quad (23)$$

is given by the relation

$$U(r) = \frac{e^{r_1 r} - e^{r_2 r}}{e^{r_1 a} - e^{r_2 a}}; \quad r_{1,2} = \frac{-\alpha \pm \sqrt{\alpha^2 + 4\beta}}{2\alpha}, \quad (24)$$

where $\beta = (M + i\omega)(1 + i\omega We)$. Introducing $U(r)$ from Eq. (24) in (22) one finds that

$$w_{com}(r, t) = \frac{e^{r_1 r} - e^{r_2 r}}{e^{r_1 a} - e^{r_2 a}} e^{i\omega t}; \quad 0 < r < a, \quad t \in R. \quad (25)$$

Now, bearing in mind the notation $(15)_1$ and coming back to the initial variables, it results that the permanent dimensionless velocity fields $w_{cp}(z, t)$ and $w_{sp}(z, t)$ corresponding to the MHD modified second problem of Stokes for ECUCIMFs are given by the relations

$$w_{cp}(z, t) = Re \left\{ \frac{[\alpha(1-z)+1]^{r_1} - [\alpha(1-z)+1]^{r_2}}{(\alpha+1)^{r_1} - (\alpha+1)^{r_2}} e^{i\omega t} \right\}; \quad (26)$$

$$0 < z < 1, \quad t \in R,$$

$$w_{sp}(z, t) = Im \left\{ \frac{[\alpha(1-z)+1]^{r_1} - [\alpha(1-z)+1]^{r_2}}{(\alpha+1)^{r_1} - (\alpha+1)^{r_2}} e^{i\omega t} \right\}; \quad (27)$$

$$0 < z < 1, \quad t \in R.$$

The corresponding permanent shear stresses, namely

$$\tau_{cp}(z, t) = -\alpha Re \left\{ \frac{r_1[\alpha(1-z)+1]^{r_1+1} - r_2[\alpha(1-z)+1]^{r_2+1}}{(\alpha+1)^{r_1} - (\alpha+1)^{r_2}} \frac{e^{i\omega t}}{1+i\omega We} \right\}; \quad (28)$$

$$0 < z < 1, \quad t \in R,$$

$$\tau_{sp}(z, t) = -\alpha Im \left\{ \frac{r_1[\alpha(1-z)+1]^{r_1+1} - r_2[\alpha(1-z)+1]^{r_2+1}}{(\alpha+1)^{r_1} - (\alpha+1)^{r_2}} \frac{e^{i\omega t}}{1+i\omega We} \right\}; \quad (29)$$

$$0 < z < 1, \quad t \in R,$$

have been determined using the relations (15), (17) and (25). Direct computations show that $w_{cp}(z, t)$, $\tau_{cp}(z, t)$ and $w_{sp}(z, t)$, $\tau_{sp}(z, t)$ given by the above relations satisfy both the governing equations (10), (11) and the boundary

conditions (14). Furthermore, making $M = We = 0$ in Eqs. (26) and (27), the dimensionless velocity fields (41) and (42) obtained by Fetecau and Agop [7] for incompressible Newtonian fluids with pressure-dependent viscosity are recovered.

Now, for a check of the above results, let us remember that recently Fetecau [6] has determined the permanent dimensionless velocity and shear stress fields corresponding to the MHD modified Stokes second problem for ordinary ECUCIMFs. Their expressions are given by the relations

$$w_{ocp}(z, t) = Re \left\{ \frac{\sinh \left[(1-z) \sqrt{(M+i\omega)(1+i\omega We)} \right]}{\sinh \left[\sqrt{(M+i\omega)(1+i\omega We)} \right]} e^{i\omega t} \right\}; 0 < z < 1, t \in R, \quad (30)$$

$$w_{osp}(z, t) = Im \left\{ \frac{\sinh \left[(1-z) \sqrt{(M+i\omega)(1+i\omega We)} \right]}{\sinh \left[\sqrt{(M+i\omega)(1+i\omega We)} \right]} e^{i\omega t} \right\}; 0 < z < 1, t \in R, \quad (31)$$

$$\tau_{ocp} = -Re \left\{ \frac{\cosh \left[(1-z) \sqrt{(M+i\omega)(1+i\omega We)} \right]}{\sinh \left[\sqrt{(M+i\omega)(1+i\omega We)} \right]} \frac{\sqrt{M+i\omega}}{\sqrt{1+i\omega We}} e^{i\omega t} \right\}; \quad (32)$$

$$0 < z < 1, t \in R,$$

$$\tau_{osp} = -Im \left\{ \frac{\cosh \left[(1-z) \sqrt{(M+i\omega)(1+i\omega We)} \right]}{\sinh \left[\sqrt{(M+i\omega)(1+i\omega We)} \right]} \frac{\sqrt{M+i\omega}}{\sqrt{1+i\omega We}} e^{i\omega t} \right\}; \quad (33)$$

$$0 < z < 1, t \in R.$$

Figures 1 and 2 (see below) show that the diagrams of $w_{cp}(z, t)$, $w_{sp}(z, t)$ and $\tau_{cp}(z, t)$, $\tau_{sp}(z, t)$ tend to superpose over those of $w_{ocp}(z, t)$, $w_{osp}(z, t)$ and $\tau_{ocp}(z, t)$, $\tau_{osp}(z, t)$, respectively, when the pressure-viscosity coefficient $\alpha \rightarrow 0$.

3.2 Modified Stokes first problem

Let us suppose that, in the same conditions as before, the lower plate begins to slide in its plane with the constant velocity W after the initial moment $t = 0$. The fluid begins to move and its motion corresponds to the MHD modified Stokes first problem for ECUCIMFs. The dimensionless permanent velocity and shear stress fields corresponding to this problem can be immediately obtained taking $\omega = 0$ in Eqs. (26) and (28).

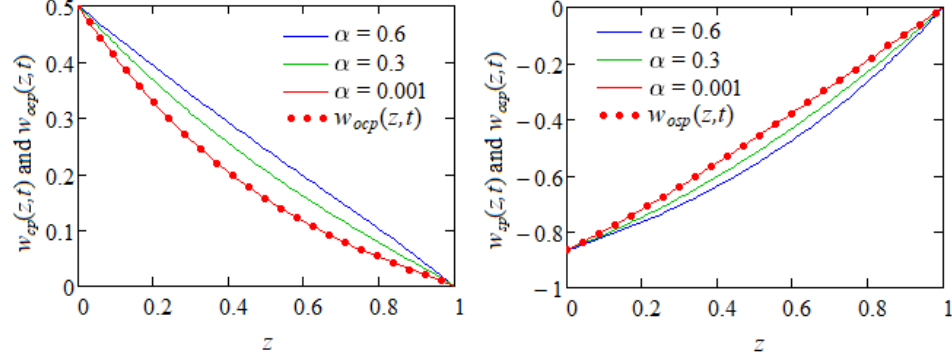


Figure 1: Convergence of the dimensionless permanent velocities $w_{cp}(z, t)$ and $w_{sp}(z, t)$ to $w_{ocr}(z, t)$ and $w_{osp}(z, t)$, respectively, at the moment $t = 5$ when $\omega = \frac{\pi}{3}$, $M = 0.8$, $We = 0.7$ and decreasing values of the parameter α .

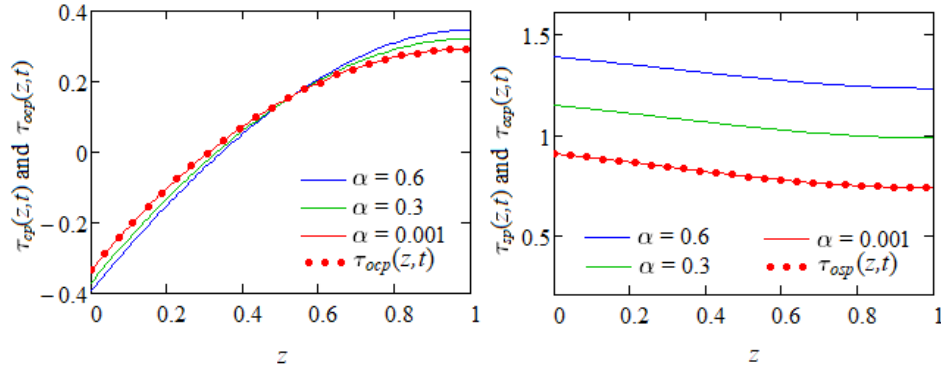


Figure 2: Convergence of the dimensionless permanent velocities $\tau_{cp}(z, t)$ and $\tau_{sp}(z, t)$ to $\tau_{ocr}(z, t)$ and $\tau_{osp}(z, t)$, respectively, at the moment $t = 5$ when $\omega = \frac{\pi}{3}$, $M = 0.8$, $We = 0.7$ and decreasing values of the parameter α .

Their expressions, given by the relations

$$w_{Cp}(z) = \frac{[\alpha(1-z)+1]^{q_1} - [\alpha(1-z)+1]^{q_2}}{(\alpha+1)^{q_1} - (\alpha+1)^{q_2}}; \quad 0 < z < 1, \quad (34)$$

$$\tau_{Cp}(z) = -\alpha \frac{q_1[\alpha(1-z)+1]^{q_1+1} - q_2[\alpha(1-z)+1]^{q_2+1}}{(\alpha+1)^{q_1} - (\alpha+1)^{q_2}}; \quad 0 < z < 1, \quad (35)$$

are same both for Newtonian and Maxwell fluids. This is possible since, for such motions, the governing equations are identical for the two types of fluids. In the last two relations $q_{1,2} = \left(-\alpha \pm \sqrt{\alpha^2 + 4M}\right)/(2\alpha)$. In the absence of magnetic field, the corresponding permanent dimensionless solutions

$$w_{Cp}(z) = \frac{(1+\alpha)(1-z)}{1+\alpha(1-z)}, \quad \tau_{Cp} = -(\alpha+1), \quad (36)$$

have been determined taking the limits of the relations (34) and (35) when $M \rightarrow 0$. Of course, these solutions can be directly obtained solving the boundary value problem corresponding to this motion. It is worth to mention the fact that the shear stress τ_{Cp} , unlike the fluid velocity that is a function of the spatial variable y , is constant on the entire flow domain. Finally, taking $\alpha = 0$ in Eqs. (36) the classical solutions

$$w_{Cp}(z) = 1 - z, \quad \tau_{Cp} = -1, \quad (37)$$

are recovered.

4 Some graphical representations and discussions

In the previous section, analytical expressions of the permanent dimensionless velocity and shear stress fields corresponding to modified Stokes problems for some ECUCIMFs with pressure-dependent viscosity have been derived in terms of Weissenberg number We , magnetic parameter M and the pressure-viscosity coefficient α . The obtained results, like in many other previous works, can be used to determine the required time to reach the steady or permanent state for the respective motions. Here, in order to bring to light some physical insights of the obtained results, Figures 3 and 4 are included to underline the oscillatory behavior of the fluid motion in the case of the second problem of Stokes and to show the variations of the fluid velocity with respect to the magnetic field M and the pressure-viscosity coefficient α .

In Figure 3, in which the variations in time of $w_{cp}(z, t)$ and $w_{sp}(z, t)$ at the middle of the channel are presented at three values of the Weissenberg

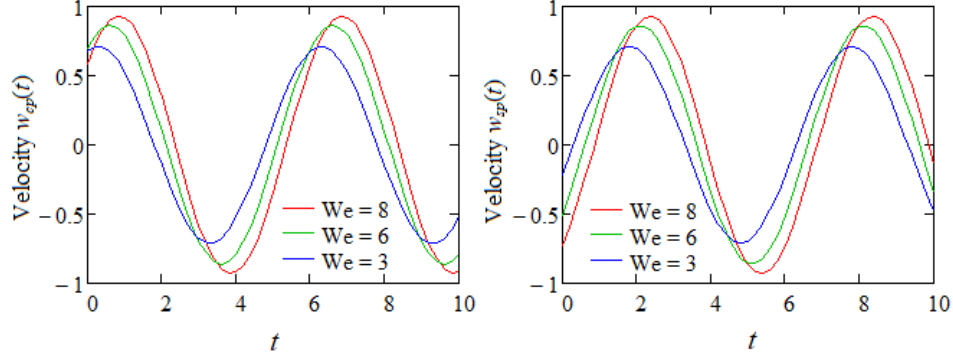


Figure 3: Time variations of the dimensionless permanent velocities $w_{cp}(z, t)$ and $w_{sp}(z, t)$ given by Eqs. (26) and (27) at the middle of channel ($z = 0.5$) when $\omega = \frac{\pi}{3}$, $\alpha = 0.5$, $M = 0.8$ at three values of Weissenberg number We .

number We and fixed values for the other parameters, it is clearly visualized the oscillatory behavior of the two motions and the phase difference between them. In the same time, as expected, the maximum values of the oscillations amplitude corresponding to the two motions are identical at same values of physical parameters and increase for increasing values of the Weissenberg number We . This means that the Maxwell fluids flow faster in comparison with Newtonian fluids.

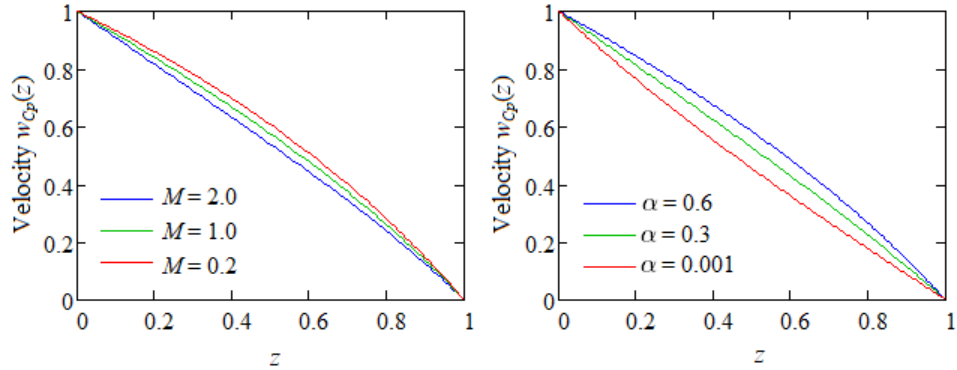


Figure 4: Profiles of the dimensionless permanent velocity $w_{cp}(z)$ given by Eq. (34) for $\alpha = 0.6$ and three values of M , and $M = 0.8$ at three values of α .

Figures 4, in which are presented profiles of the dimensionless perma-

nent velocity field $w_{Cp}(z)$ at decreasing values of the parameter M or α , clearly show that the fluid velocity is an increasing function with regard to the pressure-viscosity coefficient α and declines for increasing values of the magnetic parameter M . Consequently, the fluids with pressure-dependent viscosity flow faster in comparison with ordinary fluids and their velocity diminishes in the presence of a magnetic field.

5 Conclusions

In this work the modified Stokes problems for a class of ECUCIMFs with power-law dependence of viscosity on pressure were investigated in the presence of a constant magnetic field. The influence of gravitational acceleration was also taken into consideration and some known results from the literature have been recovered as limiting cases of present solutions. Graphical representations have been used to validate the obtained results and to bring to light some characteristics of the fluid motion. The main results that have been here obtained are:

- Closed form expressions have been established for the dimensionless permanent velocity and shear stress fields of the MHD modified Stokes problems for a class of ECUCIMFs with pressure-dependent viscosity.
- Obtained solutions satisfy the governing equations and boundary conditions and reduce to known results from the existing literature in limiting cases.
- Permanent shear stress for MHD modified Stokes' first problem is constant on the entire flow domain although the corresponding velocity is function of the spatial variable.
- The fluids with pressure-dependent viscosity flow faster than ordinary fluids and in the presence of a magnetic field their velocity diminishes.

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