Journal of the Technical University of Gabrovo

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THE ANALYSIS OF INTERACTION OF INERTIA FORCES AND MASS FORCES WHICH HAVE MAGNETIC NATURE IN UNSTABLE MECHANICAL AND BIOLOGICAL FLOWS

A.N. Mamedov[1], S.V. Stas*[2], Ya.A. Honcharova[1], O.M. Yakhno[1]

[1] *National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"*

[2] *Cherkasy Institute of Fire Safety named after Chornobyl Heroes of National University of Civil Defence of Ukraine*

ARTICLE INFO

Article history:
Received 27 August 2019
Accepted 21 November 2019

Keywords:
inertia forces, magnetic field, viscosity, initial section, pressure, velocity field

ABSTRACT

As we known, unstable flows in the field of inertia due to convective acceleration and viscous friction are widely used in hydraulic systems. But in the same time, the bad studied flow of electrically conductive liquids remains under conditions when an additional effect on the flow forces with a magnetic nature arises a flow in the cross section. Essentially relevant and insufficiently studied problem is the behavior of liquids in the initial section, which has the following forms. Shown that in the absence of inertia forces from convective acceleration (in the Stokes flow) the velocity diagram depends only on the rheological properties of the fluid.

In this work we identifies the conditions under which the magnetic field contributes to the inhibition of the flow in the channel; Cases where the fluid exhibits an anomaly are considered and data on the determination of the velocity and stress fields are obtained. Physical modeling was carried out using capillary viscometers of various diameters. Rheological studies have shown that the fluids which were in use can be described by the laws of Newton, Ostwald-de-Ville and Ericksen.

INTRODUCTION

Works in which we study the interaction of power and mass forces with magnetic nature in unstable mechanical and biological flows, get implementation in technical, medical, biological, chemical and other systems. For example, as we know, ferrofluids have friction-reducing capabilities. Author O. N. Labkovich [1] experimentally investigated friction losses in a wide range of speedsand the possibility of their reduction in the vortex flow of a magnetic fluid in the gap between the cylinders.

Conductivity of concentrated aqueous solutions of CuSO4 has been defined by O. G. Nevernaya [2]. Dynamic viscosity and Gibbs activation energy of viscous flow were calculated for these electrolytes. The concentration dependences of these characteristics were analyzed in terms of structural transformations.

Author A.N. Lopanov in the article „Modeling of the Electrical Conductivity of Graphite Dispersions in Electrolytes" [3] states that, the main contribution to the increase in the electrical conductivity in dilute electrolytes in the alternating electric field is made by the polarization of particles due to their surface conductivity.

EXPOSITION

A number of studies are devoted to the study of viscous flow and abnormally viscous fluids, with electrical conductivity [4-9]. In most cases, the manifestation of forces with a magnetic nature is considered as the action of mass forces. The degree of their influence on the flow is determined depending on the ratio between the inertial forces from convective acceleration and forces which have a magnetic nature. In general, when an unstable flow is considered, the equation of motion is represented as:

$$\begin{cases} \rho(\vec{v}\nabla)\vec{v} = -\nabla p + \mu\Delta\vec{v} + \dfrac{1}{c}\left[\vec{j}\times\vec{B}\right], div\,\vec{v} = 0 \\ \vec{j} = \sigma\left(-\nabla\varphi + \dfrac{1}{c}\left[\vec{v}\times\vec{B}\right]\right), div\,\vec{j} = 0 \end{cases}$$

$$rot\vec{B} = \frac{4\pi}{c}\vec{j},\ div\vec{B} = 0 \quad (1)$$

First equation in this system – equation of motion, taking into account as viscous friction forces, as forces which have a magnetic nature, defined as a function of tension electric and magnetic fields. In this way, mass forces can be represented by:

$$\vec{F}_{sum} = \vec{F}_0 + \vec{F}_{pm} = \rho\vec{a} + \frac{1}{\sigma}\left[\vec{j}\times\vec{B}\right], \quad (2)$$

where $\vec{F}_0$ characterizes mass forces of non-electromagnetic origin (gravity, centrifugal forces). Second term – forces of electromagnetic origin (ponderomotive forces). Ponderomotive force is defined as a value equal to:

$$\left[\vec{j}\times\vec{B}\right] = \left(rot\vec{B}\right)\times\frac{\vec{B}}{\mu^*} = \frac{(\vec{B}\,grad\,)\vec{B}}{\mu^*} - \frac{grad\,\vec{B}}{2\mu} \quad (3)$$

* Corresponding author. E-mail: stas_serhiy@yahoo.com

where $\vec{j}$ – current density, $\vec{B}$ – magnetic field induction, μ^* - magnetic permeability. Under the conditions given in the work [5], in the flow with transverse magnetic field for large numbers of Reynolds can be used these equations:

$$\begin{cases} \rho\left(u_x\frac{\partial u_x}{\partial x}+u_z\frac{\partial u_x}{\partial z}\right)=-\frac{dp}{dx}+\mu\frac{\partial^2 u_x}{\partial x^2}-\frac{\sigma\left|\vec{B}^2\right|}{c^2}u_x+\frac{\sigma\left|\vec{E}^*(x)\right|\left|\vec{B}(x)\right|}{c} \\ \frac{\partial u_x}{\partial x}+\frac{\partial u_x}{\partial z}=0 \\ u_x=u_z=0\,npu\,z=\pm a,\ \int_{-a}^{a}u_x dz=2aU=const, \\ u_x=u_0(z)by\,x=0 \end{cases} \quad (4)$$

For the initial section in the rectangular channel with transverse magnetic field based on these equations in article [5] the following equations were formulated

$$\begin{cases} \rho\left(u_x\frac{\partial u_x}{\partial x}+u_z\frac{\partial u_x}{\partial z}\right)=-\frac{df}{dx}+\mu\frac{\partial^2 u_x}{\partial x^2}-\frac{\sigma\left|\vec{B}^2\right|}{c^2}u_x, \\ \frac{\partial u_x}{\partial x}+\frac{\partial u_x}{\partial z}=0, \end{cases} \quad (5)$$

where function f related to the characteristics of the magnetic field the following ratio

$$-\frac{df}{dx}=-\frac{dp}{dx}+\frac{\sigma\left|\vec{E}^*(x)\right|\left|\vec{B}(x)\right|}{c} \quad (6)$$

The boundary conditions are then accepted in the form

$$\begin{cases} u_x=u_z=0\,by\,z=\pm a \\ u_x=u_0(z), f=f_0\,npu\,x=0,\ \int_{-a}^{a}u_x dz=2aU \end{cases} \quad (7)$$

The presented equations can be adjusted depending on the rheological properties of the conductive fluid. For example, for the case of a power-law fluid Ostwald de Ville, will take the following form

$$u_x\frac{\partial u_x}{\partial x}+u_z\frac{\partial u_x}{\partial z}=-\frac{1}{\rho}\cdot\frac{dp}{dz}-\frac{1}{\rho x}\cdot\frac{\partial}{\partial x}\left(xk\left(\frac{\partial u_z}{\partial x}\right)^n\right), \quad (8)$$

where k consistent constant, n flow index. The solution to this equation regarding the law of distribution of speeds can imagine similar to research hydrodynamic initial section [8] as follows

$$\frac{u_x}{u_{cp}}=a\left(\frac{y}{\delta}\right)+b\left(\frac{y}{\delta}\right)^2+c\left(\frac{y}{\delta}\right)^3, \quad (9)$$

where $y=R\cdot r$, δ - boundary layer thickness, a,b,c - constant, that characterize the effect of inertia forces from convective acceleration and magnetic field.

Depending on the relationship between the amount from convective acceleration and magnitude of force, that characterize the magnetic nature, the velocity plot on the hydrodynamic initial section will be deformed. Similarity criteria analysis, derived from π - theorem, provides an opportunity to conclude, that for the hydrodynamic initial section in a magnetic field, the main similarity criteria are the number of Reynolds and Hartmann criterion.

$$R_e=\frac{u_{cp}h}{v} \quad (10)$$

$$Ha=Bd\sqrt{\frac{\sigma}{\mu}} \quad (11)$$

Depending on the relationship between these criteria can be estimated as the length of the hydrodynamic initial section, and deformations of the velocity diagram.

Researches [6, 8, 10, 11] showed, that for fluids, described by law of Ostwald de Ville, deformation of the velocity field depends on the flow indexn. The law of velocity distribution in the initial section takes the form

$$v_x=v_{x_{cp}}\left(\frac{1+3x}{1+n}\right)\cdot\left[1-\left(\frac{r}{R}\right)^{\frac{n+1}{n}}\right]-u_0 \quad (12)$$

where u_0 - function, taking into account the features of the velocity field in the initial section.

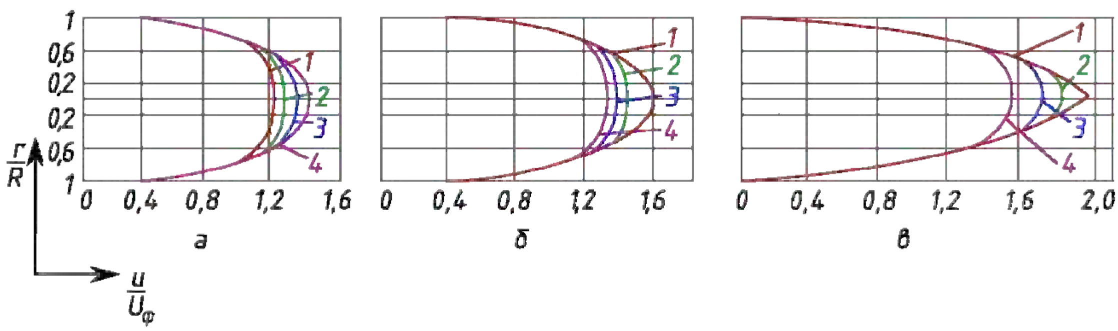


Fig. 1. Speed distribution in the initial section of a cylindrical pipe: 1.) n=1; 2.) n=0.8; 3.) n=0.6; 4.) n=0.4
а) $x=0,25x_0$; б) $x=0,5x_0$; в) $x=x_0$.

Were conducted experimental studies for determining, how the transverse magnetic field affects the deformation of the velocity plot. In them as working fluids was used conductive media, simulating fluid behavior Ostwald de Ville.

Experimental studies in which we use the two capillary method make it possible to estimate the length of the hydrodynamic initial section in the presence and absence of a transverse magnetic field. It was possible to evaluate the effect of the transverse magnetic field on the hydrodynamic resistance of the channel at various numbers of Reynolds and Hartmann based on the experiments. Fig. 2 shows, how much can the influence of the magnetic field be in laminar mode compared with case, when $\lambda = \frac{64}{Re}$.

Our studies on capillaries $d = 2,62 \div 4,35\,mm$ showed significant flow inhibition due to magnetic field. This was especially true for conductive abnormally viscous fluids, which rheological properties showed in Fig. 3.

Flow measurement at various magnetic field intensities showed at Fig. 4.

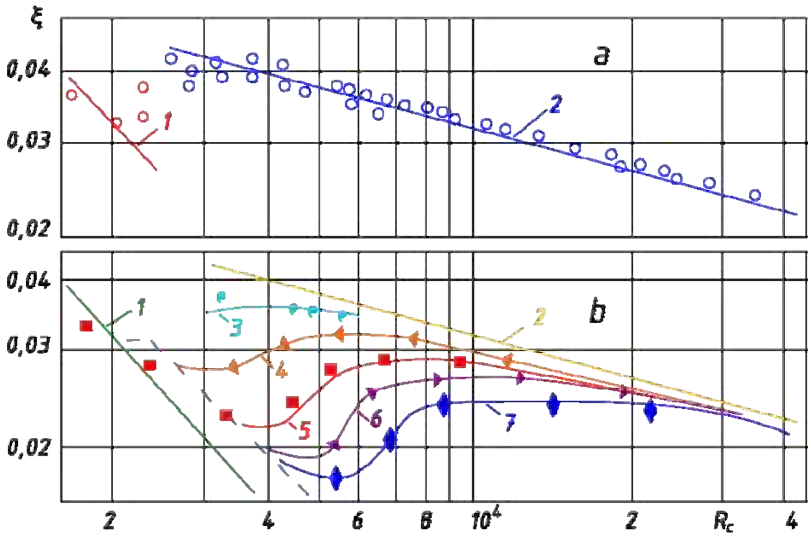


Fig. 2. Drag coefficient: a – without magnetic field; b – in the presence of a magnetic field.

$$1 - \xi = \frac{64}{Re}; 2 - \xi = \frac{0,3164}{(Re)^{0,25}}; 3 - B = 0,3\frac{Vb}{m^2}(Ha = 40,4); 4 - B = 0,5\frac{Vb}{m^2}(Ha = 66,5);$$

$$5 - B = 0,7\frac{Vb}{m^2}(Ha = 93,5); 6 - B = 0,9\frac{Vb}{m^2}(Ha = 120); 7 - B = 1,1\frac{Vb}{m^2}(Ha = 146).$$

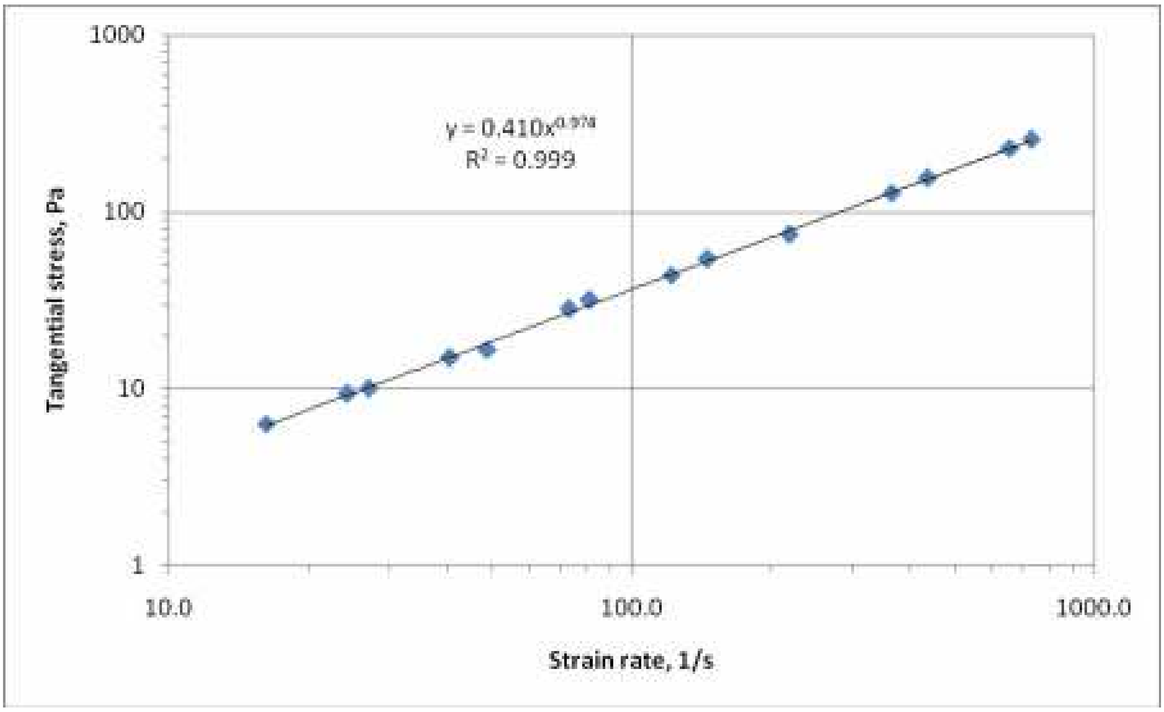
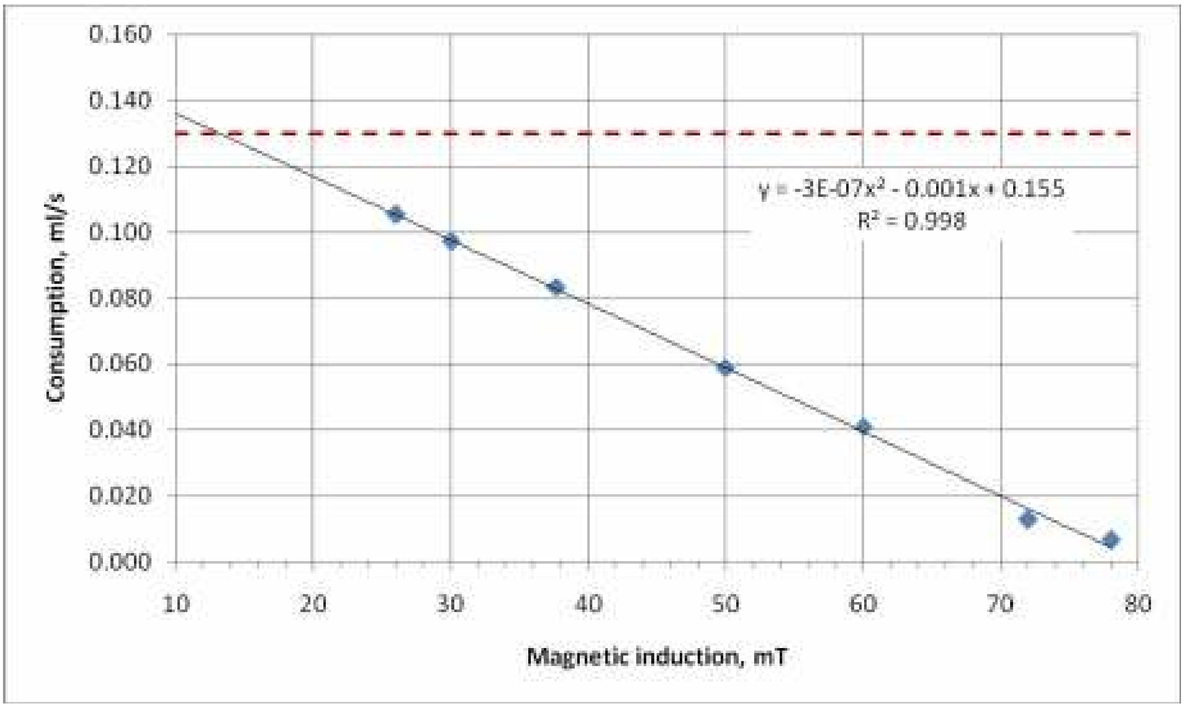


Fig. 3. Dependency graph $\tau = f(\dot{\gamma})$



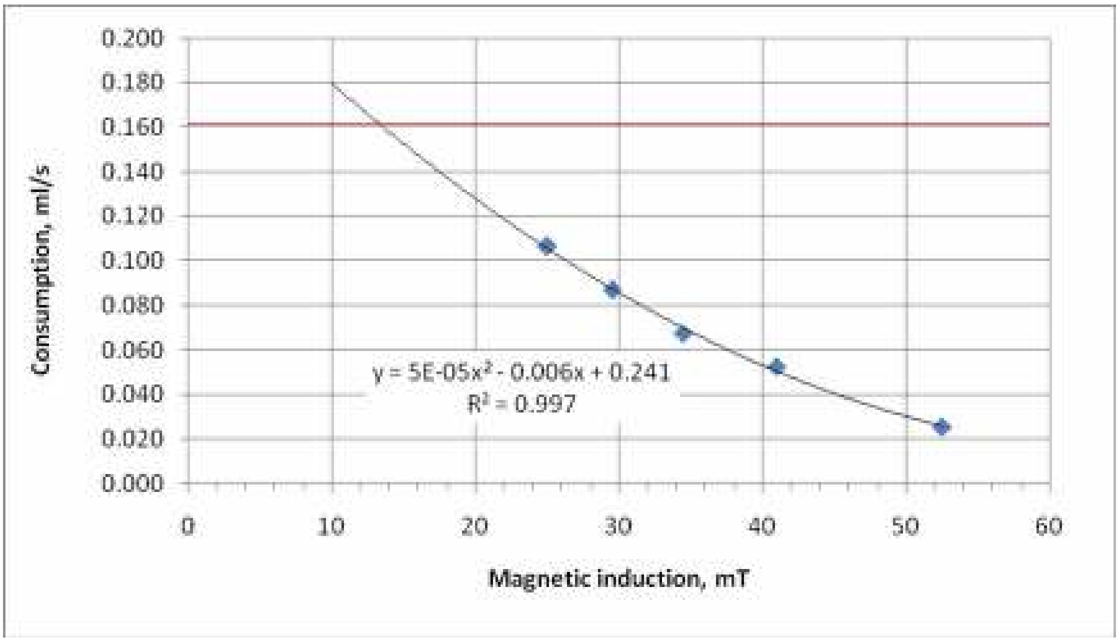


Fig. 4. Dependency graphs $Q = f(B)$

Analysis of the graph data shows, that the presence of magnetic induction leads to flow inhibition. Horizontal curves characterize flow without the influence of a magnetic field. The number of Reynolds for horizontal curves was $0{,}0219 < Re < 0{,}123$. Thus, at sufficiently low numbers of Reynolds the effect of the transverse magnetic field manifested itself significantly. Thus, it is established, that for case under consideration of a conductive non-Newtonian fluid relationship between fluid flow rate and magnetic field intensity, characterized by magnetic induction, is nonlinear and can be represented by dependency

$$Q = 0{,}0004B^2 + 0{,}0087B + 0{,}2932, \qquad (13)$$

where digital coefficients are dimensional quantities, depending on the rheological and conductive properties of the liquid. Similar results were obtained for non-Newtonian fluids Ostwald de Ville with other flow indices n. The effect of flow on the deformation of the velocity plot have significant affects on the length of the hydrodynamic initial section and strain rate of the velocity field, also it has effect on shear stress distribution in the flow of conductive fluid. The nature of this distribution is shown in the Fig. 5, where for different numbers of Hartmann is shown the change in the velocity gradient over the channel cross section.

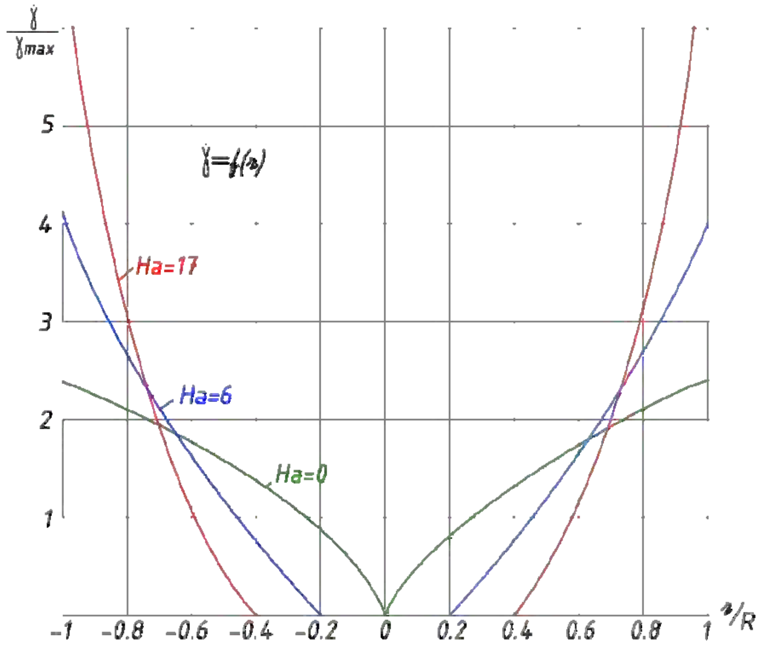


Fig. 5. With increasing number of Hartmann under the influence of a magnetic field a quasi-solid flow zone arises

As we see in the Fig. 5, with increasing number of Hartmann under the influence of a magnetic field a quasi-solid flow zone arises, characteristic for viscoplastic fluid. Using expressions for friction, a law was received, that characterizing the dependence of the coefficient of friction the number of Hartmann

$$c_f = \frac{2F_{TP}}{\rho u^2} . \tag{14}$$

CONCLUSION

In this way, it can be concluded that the magnetic field affects the friction forces in the flow of electromagnetic fluid. In conclusion, it should be noted, that analyzing the flows, the authors of the work made the following conclusions:

- pressure forces in a quasi-solid zone are balanced by volumetric force $\left[\vec{j} \times \vec{B}\right]$;
- at the boundary of the quasi-solid zone, the shear stress is zero;
- with increasing number of Hartmann the quasi-solid flow zone expands, and thus the speed profile, increasing, becomes flatter.

In this way, The article analysis the influence of the transverse magnetic field, characterized by $\left[\vec{j} \times \vec{B}\right]$ on hydrodynamic characteristics conductive flow and shown, that influence in the process of destabilization of the flow can be taken into account using the criterion of Hartmann.

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