Modeling of Deformation Processes and Flow of Highly Concentrated Suspensions in Cylindrical Pipelines

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ABSTRACT

The article discusses the improvement of mathematical modeling of deformation processes and the flow of highly concentrated suspensions (pulps) in cylindrical pipelines, taking into account the rheological model of visco-inertially deformable media introduced by I.N.Khusanov using the concept of deformation properties by inertia, which has found application to improve the efficiency of mining, concentrates and tailings for hydraulic transport. The problem is solved using finite-difference methods for vortex equations and the flow function

KEYWORDS: *Navier-Stokes equations, Visco-inert deformable media, rheological model.*

Introduction

Over the past decades, the efforts of many scientists in the field of research of multiphase flows have been aimed at creating the foundations of the theory [1-10] - mathematical modeling of flows of viscoplastic, viscoelastic, viscoelastic media based on the mechanics of multiphase media. These studies conducted by different authors have shown that they have not completely solved important problems of the mechanism of structure formation and structure destruction of multiphase media, taking into account the fundamental property of deformation inertia [11-12], and a unified theory covering the entire variety of homogeneous and heterogeneous liquid media has not yet been created.

In practice, along with a sufficient measure of viscous properties (Newtonian fluid), there are media whose stress-strain state largely depends on changes in stresses and strain rates both in time and in space. In some cases, the latter have the property of noticeably changing the stress state at constant speed or accelerated deformation (relaxation property) [11], as well as changing the deformed state at constant stress (aftereffect or retardation property). Very often, the phenomena of relaxation and retardation, known collectively as heredity, manifest themselves simultaneously even in media that are indistinguishable from quite viscous liquids during the flow, not to mention media such as concentrated mixtures (pulps), solutions, oils, pastes, oils, bitumen, etc., in which these properties are pronounced. Relaxation and retardation transitions in mixtures are manifested at different levels of their molecular and molar organization. By the term "mole" we mean more representative particles consisting of a large number of molecules of both homogeneous and inhomogeneous medium in physical and mechanical behavior, which manifest themselves as an integral formation. In this regard, we consider the medium in question to consist of two parts, with one part consisting of disordered, unconnected smallest particles, and the second of connected segments and represents structured micro–areas distributed throughout the volume – moths of various types. Different types of moths are characterized by correspondingly different lifetimes. When the voltage changes, the number of particles is redistributed between the structured and unstructured parts of the medium, i.e. the relative volume content of free particles and moles changes. Mixtures, in particular, dispersed systems, are characterized by the fact that their structure is described by a model according to which there are liquid and solid phases. Particles of the solid phase, binding to liquid molecules and nearby solid phase particles, in our understanding of moles, both individually and in a connected aggregate, are moles, but more durable than moles consisting of liquid particles.

Visco-inert deformable media are liquids, some of which form a continuous visco-deformable phase, and some are liquid particles combined in moles as in a turbulent flow (whose dimensions can range from several hundred microns to several hundred meters, having different shapes and masses) and liquids in which particles and their friction-related, larger kinetic formations are dispersed. At the same time, molecular formations and dispersed particles, as well as their associated complexes in the liquid, will be called moles. These mixtures are deformed, in addition to the viscous and elastic mechanism, also by deformation inertia [11]. In this case, relatively small aggregates of particles can provide an increase in irreversible viscous deformation associated with deformation inertia or, conversely, can delay it for the same reason if they, resisting due to deformation inertia or the same viscous lagging deformation, move in the current. For an undeformed medium, the processes of breaking and restoring physical nodes (bonds) during the thermal movement of molecules and moles are mutually balanced, and after the application of the load, the equilibrium is disturbed and the process of directed rearrangement of nodes and chains begins with the formation and destruction of kinetic units of various sizes and shapes. As a result, in such environments we will have a wide set of relaxation and retardation times spanning several orders of magnitude. Based on these data, we can determine almost all the physical and mechanical properties of media associated with the processes of relaxation and retardation occurring in them.

Deep processing of deposits leads to an increase in the yield of solid tailings of enrichment of the smallest particles, which, with an increase in their concentration in the hydraulic mixture, contribute to the transformation of Newtonian liquids into non-Newtonian, rheologically complex fluids. In the field of the theory of hydrotransportation, great achievements belong to scientists - M.A. Velikanov, who substantiated the gravitational theory of motion of the solid phase of a suspended flow, and V.M. Makkaveev with his diffusion theory of pulsation motion of solid particles in a fluid flow. The research carried out by scientists N.A. Silin, A.P. Yufin, M.A. Dementiev, V.N. Pokrovskaya, A.E. Smoldyrev, A.G. Jvarsheishvili and others is of great importance in expanding and deepening the theoretical approach to the problem of solid transport in a liquid flow. From foreign schools, the works of R. Durand, R. Foster, D.F. Richardson, S.A. Pike, V. Pazhonki, Ts. Kemblovsky, E. Sobota, P. Slatter, V.A. Manuel and others made a great contribution to the general theory and practice of hydraulic transport [13-15].

Depending on the particle size, the conditions of hydrodynamic interaction of dispersed particles with the flow of a dispersive carrier fluid change. The following classification of hydraulic mixtures is more common in the literature: colloidal, structural, fine-dispersed, coarse-dispersed, inhomogeneous coarse-dispersed and polydisperse hydraulic mixtures, which contribute to the transformation of Newtonian liquids into non-Newtonian

Математические постановки и вычислительные методы

The analysis of the structure of the flows of hydraulic mixtures should proceed from the features of the movement of a homogeneous liquid, into which solid particles are added. With increasing concentration of solid particles in the flow, the flow structure changes depending on the physical, mechanical and rheological characteristics of the media

This complex retarding rheological model in tensor form has the form [11]:

$$\tau_{ij} = \mu\dot{\gamma}_{ij} + m_\ell\ddot{\gamma}_{ij} \qquad (1)$$

where $\tau_{ij}, \dot{\gamma}_{ij}$ и $\ddot{\gamma}_{ij}$ - stress tensors, strain rates and a new concept of change in strain rate, i.e. acceleration of deformation, as well as μ and m_ℓ – the coefficients of proportionality, called, respectively, dynamic viscosity and linear density.

The law of conservation of mass, i.e. the continuity equation in cylindrical coordinates, has the form

$$\frac{\partial u_r}{\partial r}+\frac{u_r}{r}+\frac{1}{r}\frac{\partial u_\varphi}{\partial \varphi}+\frac{\partial u_z}{\partial z}=0, \qquad (2)$$

Где μ, u_i, τ_{ij}, p – accordingly, dynamic viscosity, velocity components, stress tensor components, pressure, respectively.

Solution method

Assuming that the fluid consists of an incompressible viscous Newton fluid and a medium deformed accelerated by inertia and moving under a common pressure P, according to (1), taking into account (2), the total stress components in cylindrical coordinates can be written as

$$\tau_{ii}=-P;\ \ \tau_{r\varphi}=\mu\left(\frac{1}{r}\frac{\partial u_r}{\partial \varphi}+\frac{\partial u_\varphi}{\partial r}-\frac{u_\varphi}{r}\right)+m_\ell\left(\frac{1}{r}\frac{\partial w_r}{\partial \varphi}+\frac{\partial w_\varphi}{\partial r}-\frac{w_\varphi}{r}\right); \qquad (3)$$

$$\tau_{\varphi z}=\mu\left(\frac{\partial u_\varphi}{\partial z}+\frac{1}{r}\frac{\partial u_z}{\partial \varphi}\right)+m_\ell\left(\frac{\partial w_\varphi}{\partial z}+\frac{1}{r}\frac{\partial w_z}{\partial \varphi}\right);\ \tau_{zr}=\mu\left(\frac{\partial u_z}{\partial r}+\frac{\partial u_r}{\partial z}\right)+m_\ell\left(\frac{\partial w_z}{\partial r}+\frac{\partial w_r}{\partial z}\right),$$

where m_ℓ, w_i – linear density and acceleration components.

The equations of momentum of motion in a cylindrical coordinate system have the following form [1,16 20]: $\rho\frac{\partial u_r}{\partial t}+\rho u_r\frac{\partial u_r}{\partial r}+\rho\frac{u_\varphi}{r}\frac{\partial u_r}{\partial \varphi}+\rho u_z\frac{\partial u_r}{\partial z}-\rho\frac{u_\varphi^2}{r}=\frac{\partial \tau_{rr}}{\partial r}+\frac{1}{r}\frac{\partial \tau_{r\varphi}}{\partial \varphi}+\frac{\partial \tau_{rz}}{\partial z}+\frac{\tau_{rz}-\tau_{\varphi\varphi}}{r}+\rho F_r$

$$\rho\frac{\partial u_\varphi}{\partial t}+\rho u_r\frac{\partial u_\varphi}{\partial r}+\rho\frac{u_\varphi}{r}\frac{\partial u_\varphi}{\partial \varphi}+\rho u_z\frac{\partial u_\varphi}{\partial z}+\rho\frac{u_r u_\varphi}{r}=\frac{\partial \tau_{\varphi r}}{\partial r}+\frac{1}{r}\frac{\partial \tau_{\varphi\varphi}}{\partial \varphi}+\frac{\partial \tau_{\varphi z}}{\partial z}+\frac{2\tau_{r\varphi}}{r}+\rho F_\varphi, \qquad (4)$$

$$\rho\frac{\partial u_z}{\partial t}+\rho u_r\frac{\partial u_z}{\partial r}+\rho\frac{u_\varphi}{r}\frac{\partial u_z}{\partial \varphi}+\rho u_z\frac{\partial u_z}{\partial z}=\frac{\partial \tau_{zr}}{\partial r}+\frac{1}{r}\frac{\partial \tau_{z\varphi}}{\partial \varphi}+\frac{\partial \tau_{zz}}{\partial z}+\frac{\tau_{яr}}{r}+\rho F_z,$$

$$\rho\frac{\partial u_r}{\partial t}+\rho u_r\frac{\partial u_r}{\partial r}+\rho\frac{u_\varphi}{r}\frac{\partial u_r}{\partial \varphi}+\rho u_z\frac{\partial u_r}{\partial z}-\rho\frac{u_\varphi^2}{r}=-\frac{\partial p}{\partial r}+$$

$$+\mu\left(\frac{\partial^2 u_r}{\partial r^2}+\frac{\partial u_r}{r\partial r}+\frac{\partial^2 u_r}{\partial z^2}-\frac{u_r}{r^2}\right)+m_\ell\left(\frac{\partial^2 w_r}{\partial r^2}+\frac{\partial w_r}{r\partial r}+\frac{\partial^2 w_r}{\partial z^2}-\frac{w_r}{r^2}\right)+\rho F_r$$

$$\rho\frac{\partial u_\varphi}{\partial t}+\rho u_r\frac{\partial u_\varphi}{\partial r}+\rho\frac{u_\varphi}{r}\frac{\partial u_\varphi}{\partial \varphi}+\rho u_z\frac{\partial u_\varphi}{\partial z}+\rho\frac{u_r u_\varphi}{r}=-\frac{1}{r}\frac{\partial p}{\partial \varphi}+$$

$$+\mu\left(\frac{\partial^2 u_\varphi}{\partial r^2}+\frac{\partial u_\varphi}{r\partial r}+\frac{\partial^2 u_\varphi}{\partial z^2}-\frac{u_\varphi}{r^2}\right)+m_\ell\left(\frac{\partial^2 w_\varphi}{\partial r^2}+\frac{\partial w_\varphi}{r\partial r}+\frac{\partial^2 w_\varphi}{\partial z^2}-\frac{w_\varphi}{r^2}\right)+\rho F_\varphi, \qquad (5)$$

$$\rho\frac{\partial u_z}{\partial t}+\rho u_r\frac{\partial u_z}{\partial r}+\rho\frac{u_\varphi}{r}\frac{\partial u_z}{\partial\varphi}+\rho u_z\frac{\partial u_z}{\partial z}=-\cdot\frac{\partial p}{\partial z}+$$

$$+\mu\left(\frac{\partial^2 u_z}{\partial r^2}+\frac{\partial u_z}{r\partial r}+\frac{\partial^2 u_z}{\partial z^2}\right)+m_\ell\left(\frac{\partial^2 w_z}{\partial r^2}+\frac{\partial w_z}{r\partial r}+\frac{\partial^2 w_z}{\partial z^2}\right)+\rho F_z.$$

It is possible to neglect φ when the fluid flows through the pipeline, then equations (4) and (5) will have the following form:

$$\rho\frac{\partial u_z}{\partial t}+\rho u_r\frac{\partial u_z}{\partial r}+\rho u_z\frac{\partial u_z}{\partial z}+\frac{\partial p}{\partial z}=\mu\left(\frac{\partial^2 u_z}{\partial r^2}+\frac{\partial u_z}{r\partial r}\right)+m_\ell\left(\frac{\partial^2 w_z}{\partial r^2}+\frac{\partial w_z}{r\partial r}\right), \quad (6)$$

$$\rho\frac{\partial u_r}{\partial t}+\rho u_r\frac{\partial u_r}{\partial r}+\rho u_z\frac{\partial u_r}{\partial z}+\frac{\partial p}{\partial r}=\mu\left(\frac{\partial^2 u_r}{\partial r^2}+\frac{\partial u_r}{r\partial r}-\frac{u_r}{r^2}\right)+m_\ell\left(\frac{\partial^2 w_r}{\partial r^2}+\frac{\partial w_r}{r\partial r}-\frac{w_r}{r^2}\right). \quad (7)$$

The continuity equation changes in the form

$$\frac{\partial u_r}{\partial r}+\frac{u_r}{r}+\frac{\partial u_z}{\partial z}=0. \quad (8)$$

To eliminate the pressure and translate the vortex equation, we differentiate (6) by r, and (7) by z, and after some changes we get the following equations:

$$\frac{\partial\zeta}{\partial t}+u_r\frac{\partial\zeta}{\partial r}+u_z\frac{\partial\zeta}{\partial z}+\left(\frac{\partial u_r}{\partial r}\frac{\partial u_z}{\partial r}+\frac{\partial u_z}{\partial r}\frac{\partial u_z}{\partial z}\right)-\left(\frac{\partial u_r}{\partial z}\frac{\partial u_r}{\partial r}+\frac{\partial u_z}{\partial z}\frac{\partial u_r}{\partial z}\right)=$$

$$=\frac{\mu}{\rho}\left(\frac{\partial^3 u_z}{\partial r^3}-\frac{\partial u_z}{r^2\partial r}+\frac{\partial^2 u_z}{r\partial r^2}-\frac{\partial^3 u_r}{\partial z\partial r^2}-\frac{\partial^2 u_r}{r\partial z\partial r}+\frac{\partial u_r}{r^2\partial z}\right)+ \quad (9)$$

$$+\frac{m_\ell}{\rho}\left(\frac{\partial^3 w_z}{\partial r^3}-\frac{\partial w_z}{r^2\partial r}+\frac{\partial^2 w_z}{r\partial r^2}-\frac{\partial^3 w_r}{\partial z\partial r^2}+\frac{\partial^2 w_r}{r\partial z\partial r}-\frac{\partial w_r}{r^2\partial z}\right).$$

Simplifying the equations (9), we obtain them in the following form:

$$\left(\frac{\partial u_r}{\partial r}\frac{\partial u_z}{\partial r}+\frac{\partial u_z}{\partial r}\frac{\partial u_z}{\partial z}\right)-\left(\frac{\partial u_r}{\partial z}\frac{\partial u_r}{\partial r}+\frac{\partial u_z}{\partial z}\frac{\partial u_r}{\partial z}\right)=\frac{\partial u_z}{\partial r}\left(\frac{\partial u_r}{\partial r}+\frac{\partial u_z}{\partial z}\right)-\frac{\partial u_r}{\partial z}\left(\frac{\partial u_r}{\partial r}+\frac{\partial u_z}{\partial z}\right),$$

$$\left(\frac{\partial u_r}{\partial r}+\frac{\partial u_z}{\partial z}\right)\left(\frac{\partial u_z}{\partial r}-\frac{\partial u_r}{\partial z}\right)=\zeta\cdot\left(-\frac{u_r}{r}\right)=-\zeta\frac{u_r}{r}. \quad (10)$$

$$\frac{\partial^3 u_z}{\partial r^3}-\frac{\partial u_z}{r^2\partial r}+\frac{\partial^2 u_z}{r\partial r^2}-\frac{\partial^3 u_r}{\partial z\partial r^2}-\frac{\partial^2 u_r}{r\partial z\partial r}+\frac{\partial u_r}{r^2\partial z}=\frac{\partial^2\zeta}{\partial r^2}+\frac{\partial\zeta}{r\partial r}-\frac{\zeta}{r^2}. \quad (11)$$

And finally we get a non-stationary two-dimensional system of the equation of the flow of a viscous-inert fluid through a pipeline:

$$\frac{\partial\zeta}{\partial t}+u_r\frac{\partial\zeta}{\partial r}+u_z\frac{\partial\zeta}{\partial z}-u_r\frac{\zeta}{r}=\frac{\mu}{\rho}\left(\frac{\partial^2\zeta}{\partial r^2}+\frac{\partial\zeta}{r\partial r}-\frac{\zeta}{r^2}\right)+\frac{m_\ell}{\rho}\left(\frac{\partial^2\chi}{\partial r^2}+\frac{\partial\chi}{r\partial r}-\frac{\chi}{r^2}\right). \quad (12)$$

To obtain the current function for the cylindrical coordinate, we use the following equation [17-19]:

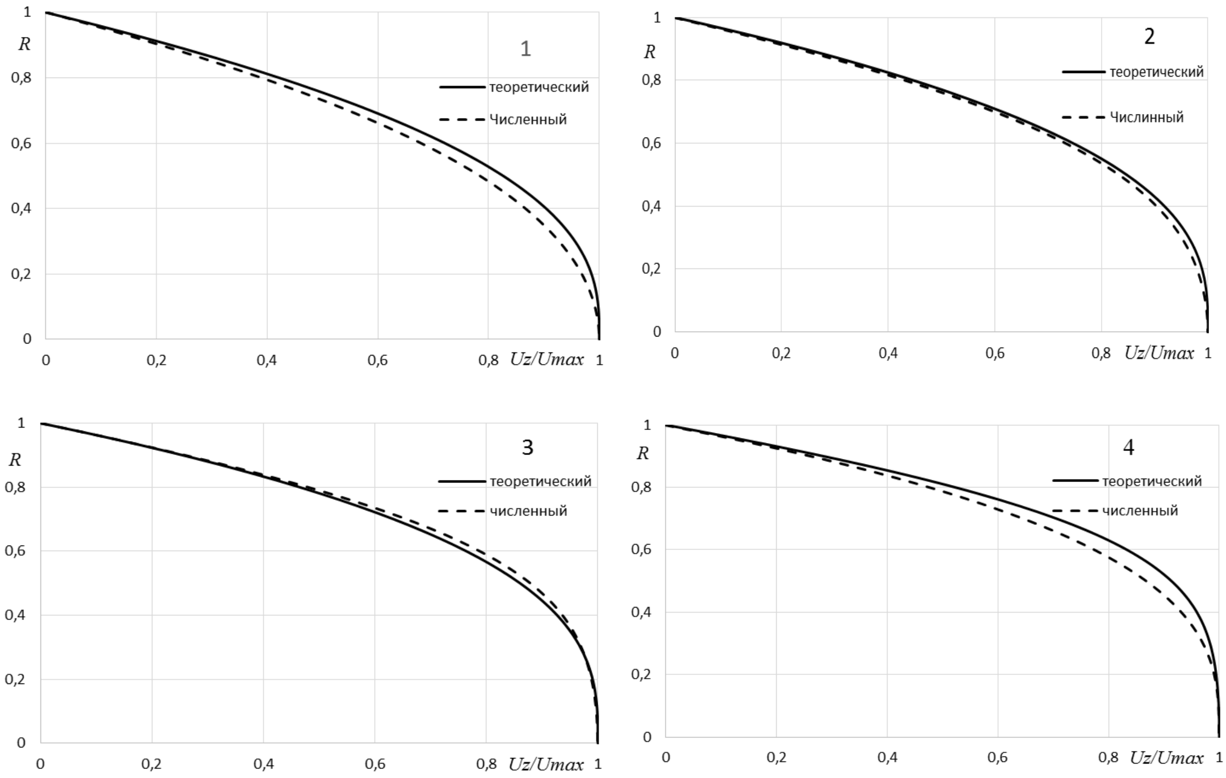
$$\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial z^2} = r\zeta. \qquad (13)$$

Due to the nonlinearity of equations (12), (13), a direct solution of the system becomes impossible and the process under consideration acquires an iterative character. To solve this problem, we use a numerical method. Equation (13) is solved by the implicit iterative Euler method. This is a first-order accuracy scheme with an approximation error of O(Δt, (Δ x)2). The Neumann stability analysis (Fourier analysis) shows that it is stable at any time step, i.e. absolutely stable. However, when using this scheme, a system of algebraic equations has to be solved at each time step [20-22].

Calculation results and their discussion

The equation is solved in the domain - {0≤r≤Hr, 0≤r≤Hz} rectangle with sides Hr and Hz, with boundary conditions of the first kind. In the future, Hr= 1 m, Hz=100 m is assumed, with boundary conditions set as follows [23-25]:

$$\begin{cases} \psi(i,j) = r_j^2/2, \psi(i,0) = 0, Vr(i,0) = 0, Vz(i,0) = 0, Vz(i,0) = Vz(i,1), \\ \alpha(Hr-1) = 0, \beta(Hr-1) = 0.5, \psi(i,Hr) = 0.5. \end{cases} \qquad (14)$$



Comparative velocity plots: theoretical, one-dimensional and numerical, two-dimensional at mℓ: 1 – 0.005; 2 – 0.25; 3 – 1; 4 – 2.5

To verify the correctness of the constructed algorithm and program, the calculated data were compared with the analytical results. Figure 1-4 shows the plots of the longitudinal velocity for unsteady two-dimensional flows of visco-inert deformable media through a circular pipeline for different values of linear density mℓ and compared with the one-dimensional stationary case at *Re*=*UHr*/*μ*=100.

As can be seen from m_ℓ=0.005, the analytical and numerical velocity plots are almost the same, and they correspond to the Poiseuille parabolic form for viscous media, since at very low m_ℓ. And starting с m_ℓ=1 to 2.5, it is clearly seen that when the value increases m_ℓ a core gradually appears in velocity plots, this can be explained by the fact that when flows of visco-inertly deformable media through a pipe as viscoplastic, the Bingham medium and the other core of the currents do not keep up with the fast flow. It can also be noted here that the analytical and numerical velocity plots almost coincide.

Conclusion

Thus, the proposed mathematical model of multiphase media through pipelines, taking into account inertia deformation, is in good agreement with the test problem, i.e. with a one-dimensional stationary flow of a visco-inert medium through pipes. At small M течение, the flow turns into a viscous Poiseuille flow, and at sufficiently large mℓ, by a special case, into a viscoplastic flow. An increase or decrease in the concentration of inert deformable media during movement is associated with a decrease or increase in the concentration of viscous media, an increase in the former is associated with the formation of supramolecular structures, and a decrease is associated with the destruction of these structures. The greater the concentration of inert deformable media, the more the medium is deformationally inert and resists movement. These results are also consistent with the obvious fact that molar formations are more inert to changes in their deformation state than molecules whose mobility is much greater relative to moles. Therefore, in media with large values of moles involved in internal exchange, there is greater resistance relative to viscous liquids.

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