Influence of Rheology on Pressure Losses in Hydrotransport System of Polymetallic Ores Tailings

S Yu Avksentiev, A K Nikolaev

Saint-Petersburg Mining University, 2, 21st Line, St Petersburg 199106, Russia

E-mail: avksentiev@mail.ru

Abstract. An important trend in mining production intensification, increasing its efficiency and competitiveness in the conditions of modern market relations, is creating a robust transportation basis that could significantly increase the performance of the transportation system with simultaneous reduction of transportation prime cost of minerals and products of their processing. Developing this basis is related to implementing continuous means of transportation among which hydraulic pipeline transport is most common in the mining industry. The calculation of head losses and flow friction characteristic is one of the most important tasks in designing hydrotransport systems. The efficiency of a hydrotransport system depends on solving this task. To reduce the energy consumption and specific amount of metal in a transportation system, mineral processing companies transport processing products in concentrated condition. Such hydraulic fluids typically show initial shear stress ($\tau_0$) and effective dynamic viscosity ($\eta_{eff}$), as well as other rheological characteristics that affect the primary parameters of hydrotransport, including head losses.

1. Introduction
In ideal viscoplastic fluids (Bingham fluids), viscoplastic properties are conditioned by physical and chemical structure of the fluid when the volume is deformed in the presence of gradient of concentration, temperature and the amount of motion, and shear resistance to fluid layers occur. Individual molecular chains change their length and shape [1]. Changing the shape and length of molecular chains causes a plastic layer shear during the initial moment of time, which causes the initial shear stress $\tau_0$ to occur. When the opportunities of changing the length and shape of individual molecular chains are exhausted, one will see a shear of individual layers of plastic, and the plastic friction law will become effective according to the Bingham model. An example of liquids similar to Bingham plastic are polymers and their solutions [2].

2. Materials and methods
When mixing a liquid, continuous, and solid discrete medium, a new continuous medium is formed, a suspension with the properties differing from its components taken separately. Every particle of the small-fraction solid phase in the aqueous medium receives a liquid shell on its surface, which results in a dipole to be formed that carries a positive and negative charges. The dipole orientation in the fluid volume is defined by their interaction. As a result of this interaction, a structure is formed, and the suspension can be regarded as a continuous
media. When the force $F$ acts on the volume of this fluid, solvate shells of dipoles are initially deformed and the initial shear resistance $\tau_0$ occurs, which in this case is caused by an elastic strain. Individual layers of the hydraulic fluid are sheared and the plastic viscosity occurs. This mechanism of viscoplastic properties demonstration is typical of the fluids that include small and almost homogeneous particles, such as kaolin hydraulic fluid [3,4].

Real fluids include particles of small classes, but heterogeneous in shape. Therefore, some solid particles will not be fully covered with a solvate shell or will lose it. In case of volume deformation of this suspension, viscoplastic friction is added by purely mechanical friction of particles that have lost it or failed to obtain solvate shells on its surface [5]. The viscosity in these fluids is manifested as a total effect of plastic viscosity caused by the shear resistance of individual hydraulic fluid layers and by the friction resistance of solid particles that have no solvate shells. Consequently, viscoplastic properties in the volume of suspensions are related to their physical (dipole formation) and mechanical (friction) nature. In accordance with this model of viscoplastic friction occurrence, occurring resistances can be associated with some effective (apparent) viscosity according to the formula [3].

$$\eta_{ef} = \eta_t \cdot k_{st} \quad (1)$$

where $\eta_{ef}$ = effective viscosity (viscosity from total effect), $k_{st}$ = coefficient structure.

Consequently, the viscosity coefficient depends on the structural viscosity $\eta_s$ that will be associated with the effective viscosity through the following ratio

$$\frac{\eta_{st}}{\eta_{st}} = k_s \quad (2)$$

where $k_s$ = plastic viscosity coefficient.

Every component of effective viscosity is defined by its own shear angle (Fig. 1).

Due to the abnormal (in relation to the Bingham model) manifestation of plastic properties, such fluids can be referred to a class of Bingham pseudoplastics [4].

![Figure 1](image1.png)

**Figure 1.** Dependency of shear resistance and viscosity on the deformation rate gradient for small-fraction hydraulic fluids

![Figure 2](image2.png)

**Figure 2.** Dependency of effective viscosity components on the concentration of coal particles
As the concentration of solids grows, the Newton viscosity increases, and with some limit concentration — structural properties do. The ratio between plastic and structural viscosity is determined from the formulas (1) and (2), where one obtains:

$$\eta_s = \eta_p \cdot \frac{k_s}{k_p}.$$  \hspace{1cm} (3)

The effective viscosity expresses a mean viscosity and is a function of the mean concentration of solid particles and the suspension flow cross-section. The structural viscosity is manifested in case of plastic deformation of the hydraulic fluid volume at the border of the flow core, and it is constant in magnitude and has the maximum value [6]. The plastic viscosity effect occurs in case of the deformation of hydraulic fluid layers and depends on the structural viscosity in its value. The formulas result in $k_s > 1$, and $k_s < 1$. If $\frac{k_s}{k_p} = 1$, then $\eta_s = \eta_p$, and, consequently $\eta_s = \eta_p$, e.g., in this case, the hydraulic fluid represents a pure liquid. The structure coefficient value, as well as the values of effective viscosity components, is defined by the concentration of solids of the tail pulp, e.g., $k_s = f(c_{st})$.

With respect to specific features of how viscoplastic properties of highly concentrated small-fraction hydraulic liquids considered above manifest themselves, the Bingham model for them can be as follows:

$$\tau = \tau_0 + \eta_p \frac{dv}{dy}.$$ \hspace{1cm} (4)

Through the structural viscosity the hydraulic fluid volume occurs, viscosity appears, along with the initial shear resistance [5].

$$\tau = \tau_0 + \eta_s \frac{k_s}{k_p} \frac{dv}{dy}.$$ \hspace{1cm} (5)

The models (4) and (5) differ from the Bingham-Shvedov model in that the effective viscosity considers both structural and plastic properties of the deformed volume of the fluid medium (hydraulic fluid).

Hydraulic fluids of tailings are formed when fine particles of iron ore are mixed with the liquids phase — water. The primary properties of formed hydraulic fluids depend on the number of particles in the volume of water accommodating them. In case of small concentrations of solids, the hydraulic fluid slightly differs from the standard Newton liquid, and the model of this suspension is the Newton viscous friction law [6].

The parameter values included into the rheological equation (23) depend on the concentration of solids in the fluid flow. For some concentration values, the initial shear stress becomes zero, as well as the structure coefficient does. In this case, the equation is transformed into the equation for Newton liquid. The equation shows that when the viscoplastic fluid flows through a pipeline $d$ in diameter, the fluid flow is divided into two zones:

- flow core characterized by the initial shear resistance of $\tau_0$, the flow core radius $r_0$ and some cross-section mean concentration of solids $c_{st}$;
- annular flow between the flow core and the pipeline wall, e.g., flow in the gap limited by internal radius $r_0$ and external radius $\frac{d}{2} = r$, so that the thickness of the annular flow zone equals $r - r_0$. The concentration of particles in the annular flow changes from the maximum mean value of $c_{st}$ at the boundary of the flow core to zero on the pipeline wall [11].

The fluid flow schematics in the pipeline cross-section are given in Figure 3. The relative dimensions of flow areas (flow core and annulus) depend on the concentration of solids. When the concentration decreases, the flow core is also decreased or may even disappear at some point. The entire pipeline cross-section is occupied by the annular zone, and the effective viscosity becomes equal to the plastic viscosity.
The structure coefficients change from 1 (at minimal concentration) to some maximum value when
the concentration is decreased. For the limit values of concentration, the structure coefficient formula
may be represented as follows.

Let us record the Shvedov-Bingham equation \( \tau = \tau_0 + \eta(c) \frac{dv}{dr} \) and differentiate it for the limit
values of tangent stresses.

When designing hydrotransport systems, the issues of solids concentration in a hydraulic fluid flow
must be solved, which will result in the lowest possible energy consumption. The expenses for
hydraulic transportation of solid materials are a complicated function of mechanical characteristics of
solid phase and hydraulic fluid. The resulted method to determine head losses and the hydraulic
resistance coefficient based on the rheology of iron ore suspension of tailings can be used in
developing a system for hydraulic transportation of iron ore tailings.

The determinants in the formula are the fluid viscosity and the concentration of solids is defined
experimentally.

3. Results
The resulted formula for hydraulic resistances differs from the known dependence for the laminar flow
of pure liquids in that its numerator has a parameter characterizing the stressed condition of the
hydraulic fluid expressed by the relation of the initial stress to the total shear stress.

The formula shows that as the relative stress increases, so does the coefficient of hydraulic
resistances.

The formula also shows that theoretical investigations and resulted dependencies do not contradict
to known and commonly accepted models of suspension flow and at the same time, it takes into
account the dependency of hydraulic resistances on the viscoplastic properties of the hydraulic fluid
defined by relative shear stress \( \sigma = \frac{\tau_0}{\tau} \).

In the final form, the head losses in the flow of concentrated hydraulic fluids having viscoplastic
properties are defined under the following expression:

\[
i_f = \lambda_f \frac{v^2_{in}}{2gD} = \frac{64}{Re} \frac{1}{1 - \sigma} \frac{v^2_{in}}{2gD},
\]  

\( \)
where \( v_m \) = average flow velocity of the hydraulic fluid.

4. Conclusions
1. The calculation has shown that the results of analytical dependencies of determining head losses and the hydraulic resistance coefficient can be taken for analysis and determining the losses along the length of non-newton liquids.
2. When the solid phase concentration in iron ore tailings hydraulic fluid increases, one can consider both viscoplastic liquids with initial shear stress \((\tau_0)\) and effective dynamic viscosity \((\eta_{eff})\) according to the adopted Bingham-Shvedov model.
3. When the solid phase concentration in a hydraulic fluid flow increases during transportation of a specific volume of solids, the specific amount of metal in the pipeline system is reduced to the decreased required pipeline diameter.

References
[1] Alexandrov V I, Kibirev V I 2016 Ore dressing 6 41-45
[2] Alexandrov V I, Avksentyev S Y, Gorelkin I M 2012 Ore dressing 3 39-42
[3] Darcy H 1957 Malet-Bachelier 10(2) 109–132
[4] Heywood N, Richardson J 1978 c1 146-152
[5] Heywood N., Alderman J 2003, Chemical Eng. Progress 4 100-107
[6] Kumar U, Singh S N, Seshadri V 2015 International Journal of Engineering and Technical Research 3(4) 394-397