DOI: 10.18454/PMI.2017.2.240

UDC 622.649

RESEARCH ON REGIMES OF LIMONITE ORE HYRDOTRANSPORT FOR THE CONDITIONS OF PERDO SOTO ALBA PLANT

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The paper examines regular flow patterns of high-concentrated limonite pulp with significant content of finest grains. Engineering procedures have been developed to calculate basic parameters of limonite ore hydrotransport in turbulent and structured regimes. Trustworthiness of scientific statements, conclusions and recommendations is justified by theoretical research, establishment of analytical dependences, results of laboratory and industrial experiments. Practical regularities of behavior have been identified for the coefficient of hydraulic resistance, depending on pulp density in the range 35-45 % in case of pulp flow in structured regime, as well as regularity of pressure losses in case of pulp flow in horizontal and inclined pipelines in turbulent regime.

***Key words*:** hydrotransport, flow regimes, limonite ore, pulp, rheological properties

***How to cite this article*:** Raul Izquierdo Pupo, Alberto Turro Breff. Research on Regimes of Limonite Ore Hydrotransport for the Conditions of Pedro Sato Alba Plant. Zapiski Gornogo instituta. 2017. Vol. 224, p. 240-246. DOI: 10.18454/PMI.2017.2.240

Introduction. Increase in production of nickel and cobalt due to opening of new nickel plants in Punta Gorda and Las Camariocas and further improvement of technological processes and equipment, used by operating enterprises, is one of the key development objectives for nickel-cobalt industry of Cuba. For 50 years the haulage of limonite ore from the quarry to Pedro Soto Alba plant has been performed by hydrotransport. However, the quarry reserves will have been depleted by 2025. Therefore today various projects are being designed to organize transportation from the new deposit Moa-East to the plant. Existing difference of geodesic altitudes (65 m) between the deposit and the point where pulp is loaded into hydroseparators is an important condition, emphasizing the possibility to use gravity transfer, as it does not consume any energy. Pedro Soto Alba plant is the only enterprise in Cuba that applies hydrotransport of limonite ore. In the pulp processing station, limonite ore is watered down to the mass concentration 25-30 %. Under the gravity particles of the size –0,833 mm are fed into the hydroseparator, using concrete and cast iron pipelines 610 mm in diameter and 5129 m in length. The pipeline is divided into 54 sections, in-between which there are wells, where velocity of the pulp decreases. The flow velocity varies in the range 1-1.4 m/s. Results of experiments have shown that settling velocity of the pulp is higher on the exit from processing station than on the entry to hydroseparator.

After hydroseparators, thickened pulp (45-48 % of solid mass) is transported with the help of centrifugal pumps; the pipeline is 460 m long and 508 mm in diameter; average flow velocity varies from 0.3 to 0.57 m/s. Apart from limonite ore, the pulp contains solid serpentine fraction (up to 5 %), which crusts at the bottom of a pipeline, reducing its useful section and causing pressure losses. Hence, when designing a new pulp processing facility, it is necessary to introduce technical measures preventing serpentine fraction from entering hydroseparators.

Preliminary estimations and practical data by other researchers suggest the presence of viscoplastic properties in the limonite pulp.

Analysis of related publications and operation of hydrotransport facilities has shown that, despite its wide application and abundance of experimental research on hydrotransport, there is still no theory and analytical model that would describe the flow structure of viscoplastic pulp. Enormous diversity of physical and mechanical properties of viscoplastic pulp and conditions of its hydrotransportation limits applicability of proposed calculation formulas, therefore in most cases it is impossible to define transportation parameters with the precision, necessary for practical purposes.

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Efficiency of hydrotransport is determined by flow velocity, concentration and pressure losses. Proposed methods of calculating these parameters are based on Shvedov-Bingham law of viscoplastic flow, derived using continuum dynamics, and require relevant adjustments, relying on experimental research of specific pulp flow.

Research methods included: analysis of literature sources, experience of operating hydrotransport facilities of limonite pulp in Cuba and scientific integration of research on fine-grain suspension-carrying flows; theoretical and experimental investigations of rheological properties and transportation parameters of limonite pulps; planning of experiments and processing of experimental data using methods of mathematical statistics and regression analysis. A procedure has been developed to calculate parameters of limonite pulp hydrotransport facility in structured and turbulent regimes [5].

Recommendations have been elaborated for the design of a new hydrotransportation line Moa-East in Pedro Soto Alba plant. Fig.1 shows distribution of flow velocity and stress in the pipeline, and Fig.2 contains a generalized rheological curve of limonite pulp [5, 9].

Results of preliminary estimations of rheological properties of limonite pulp, performed on capillary viscosimeter, demonstrate that rheological curves can be described using Bulkley-Herschel model [5]

$$\tau = \tau_0 + k\gamma^n. \quad (1)$$

To describe deformational behavior of concentrated suspensions, showing signs of viscosity anomaly, Yu.K.Safronov proposed the following dependence [6]:

$$\frac{\varphi}{\varphi_m} = k\left(\frac{\tau - \tau_0}{\tau_k - \tau_0}\right)^n, \quad (2)$$

where τ_0 – yield stress; τ_k – stress, associated with total disintegration of the structure; n – flow index; k – concentration ratio; φ – fluidity.

Taking into account that

$$\varphi = \frac{1}{\eta},$$

we obtain

$$dr = \frac{2l}{\Delta P} d\tau. \quad (3)$$

Plugging expressions (2) and (3) into Newton equation, we get

$$\tau = -\eta^{\gamma} = -\eta\frac{dU}{dr}. \quad (4)$$

1. Under stress $\tau_0 < \tau < \tau_a$ the flow occurs in structured regime with practically intact structure.

2. In stress range between τ_a and τ_k the flow occurs in transition regime with continuously disintegrating structure.

3. Under stress $\tau > \tau_k$ the flow occurs in turbulent regime

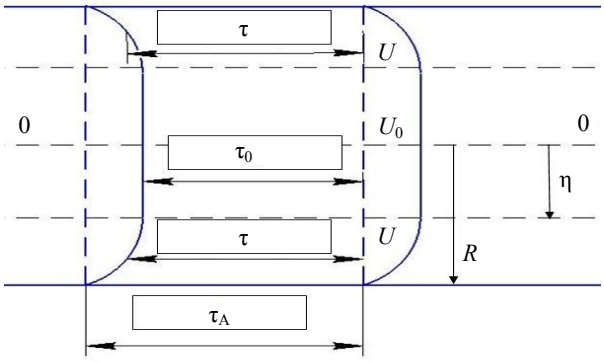


Fig.1. Distribution of flow velocity and stress in the pipeline

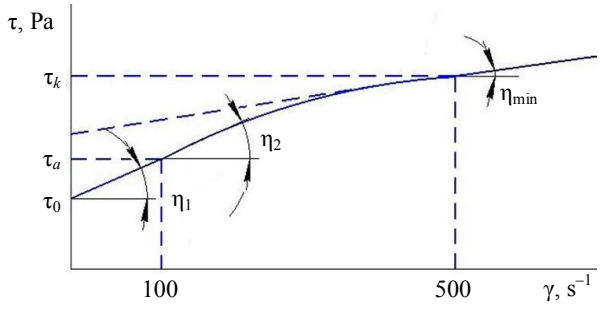


Fig.2. Generalized rheological curve of limonite pulp

$$dU = \frac{k\varphi_m}{(\tau_k - \tau_0)^n (n+1)} \left[R(\tau_R - \tau_0)^{n+1} - r(\tau - \tau_0)^{n+1} \right]; \quad (5)$$

$$U = \frac{k\varphi_m}{(\tau_k - \tau)^n (n+1)} \left[R(\tau_R - \tau_0)^{n+1} - r(\tau - \tau_0)^{n+1} \right]. \quad (6)$$

Equation (6) is correct for values $r_0 < R_0$, $r = r_0$, $\tau = \tau_0$, $U = U_0$. Velocity of the flow core equals:

$$U_0 = \frac{k\varphi_m}{(\tau_k - \tau_0)^n (n+1)} R(\tau_R - \tau_0)^{n+1}. \quad (7)$$

Pulp flow rate is expressed as follows:

$$Q = Q_1 + Q_0, \quad (8)$$

$$Q_0 = \pi r_0^2 U_0, \quad (9)$$

$$dQ_1 = 2\pi r U dr. \quad (10)$$

Plugging into equation (10) the value of velocity, calculated using formula (6), and integrating, we get the flow rate equation for annular zone Q_1. From this, overall flow rate equals:

$$Q = \frac{4\pi l k (\Delta P - \tau_0)^{n+2}}{\Delta P \eta m (\tau_k - \tau_0)^n (n+1)} \left[R r_0 + R l (\Delta P - \tau_0)^{n+1} - \frac{r_0^2}{n+2} \frac{2 r_0 l (\Delta P - \tau_0)^{n+1}}{\Delta P (n+3)} - \frac{\Delta l^2 (\Delta P - \tau_0)^{n+2}}{\Delta P^2 (n+4)} \right] +$$

$$+ \frac{\pi r_0^2 k R (\Delta P - \tau_0)^{n+1}}{\eta m (\tau_k - \tau_0)^n (n+1)}. \quad (11)$$

Obtained equation (11) allows to compute the flow rate of limonite pulp in the pipeline, depending on rheological properties of the pulp and hydraulic parameters of the flow, which can be identified by experiment.

Performed research on geologic properties of limonite pulp indicated that, when deformation gradient exceeds 500 s^{-1}, there is a direct proportion between internal shear and velocity gradient. Experiments on capillary viscosimeter showed that, when velocity gradient is lower than 100 s^{-1}, experimental dependence is graphically represented as a straight line.

Basing on the analysis carried out, it has been proposed to describe limonite pulp flow with a rheological curve, containing three sections [4, 5].

According to suggested model, limonite pulp flow is determined by a set of equations:

$$\begin{gathered} \tau = \tau_0 + \eta\gamma; \quad \tau \in [\tau_0, \tau_a], n = 1; \\ \tau = \tau_0 + k\gamma^n; \quad \tau \in [\tau_a, \tau_k]; \\ \tau = \eta_{min\gamma}; \quad \tau > \tau_k, n = 1. \end{gathered} \quad (12)$$

Pressure losses of the pulp flow can be expressed by the following dependence:

$$i = F_1\left(\mathrm{Re}, \mathrm{Y}, \frac{\Delta}{D} \right) + F_2\left(F_1, \frac{\Delta}{D}, \pi \right). \quad (13)$$

The first function F_1 in expression (13) operates with viscosity forces, the second function F_2 – with gravitational ones.

Viscosity forces are critical for the flow of viscoplastic suspensions. Thus, processing of experimental results has been performed using Reynolds (Re) and Ilyushin (I) criteria as similarity parame-

DOI: 10.18454/PMI.2017.2.240

ters for structured regime (function Δ/D). For turbulent regime viscosity forces are of secondary importance, and sometimes a dimensionless group π (function F_2) is used as similarity parameter [2].

Most researchers (V.V.Traynis, A.B.Smoldyrev, Yu.K.Safonov, V.B.Filatov and others) use simplified Buckingham equation to calculate pressure losses of viscoplastic pulp flow. From this equation after some manipulations Z.Lanzhinov and V.B.Filatov have obtained the following expression, defining coefficient of hydraulic resistance:

$$\lambda = \frac{64\left(I + \frac{\mathrm{I}}{N}\right)}{\mathrm{Re}}, \tag{14}$$

where $N = 8$. To calculate λ for limonite pulp flow it is necessary to obtain the value of N by experiment.

Pressure losses of suspension-carrying flow in turbulent regime can be retrieved from the expression:

$$i_r = i_0(l + ack_i) \tag{15}$$

where a, c, k – densities of water, solid phase and pulp; i_0 – specific pressure losses of the water flow.

For pulp transportation in inclined pipelines hydraulic slope can be defined from the formula:

$$i_{\text{н}} = i_r\,(i_r - i_0)\cos\alpha k_2, \tag{16}$$

where α – slope angle of the pipeline.

Values of coefficients K_1 and K_2 in the course of limonite pulp flow should also be estimated experimentally.

Grain size analysis of limonite ore has shown that it contains predominantly fine grains (–0.045 mm, 86.87 %), average density of the solid matter is 3400 kg/m^3.

Rheological parameters of the pulp have been measured by rotary viscosimeter RV [4-6, 9]. The method of experimental data processing is presented in the form of dependence between average velocity gradient in the gap γ and shear stress τ. Experimental rheological curves, shown in Fig.3, can be described by Shvedov-Bingham equation:

$$\tau = \tau_0 + \eta_{\text{ст}}\gamma, \tag{17}$$

where τ_0 – initial shear stress.

Examination of dependences $\tau = F\gamma$ demonstrates that limonite pulps with concentration $S > 30$ % form spatial structures [7].

Results of processing experimental data:

Concentrations	0.30	0.35	0.40	0.45
Regression equation	$\tau = 0.131\gamma$	$\tau = 0.58 + 0.152\gamma$	$\tau = 2 + 0.170\gamma$	$\tau = 5.57 + 0.194\gamma$

Investigations of hydrotransport parameters of limonite pulp have been carried out for concentrations 25, 30, 35, 40, 45 % of solid mass. After the processing of data, $i(U)$ dependences have been retrieved for pulp flow along the pipelines 100 and 150 mm in diameter (Fig.4).

It can be seen from graphs in Fig.4 that, from the position of concentration and flow velocity, hydrotransport of limonite pulp can occur in three regimes: structured, transitional and turbulent. Thus, experimental data confirm results of earlier tests on viscosimeters and a proposed physico-mathematical model.

Executed experimental tests allowed to estimate values of coefficients k_1, k_2 and N: $k_1 = 3.31$; $k_2 = 4.53$; $N = 2.3$.

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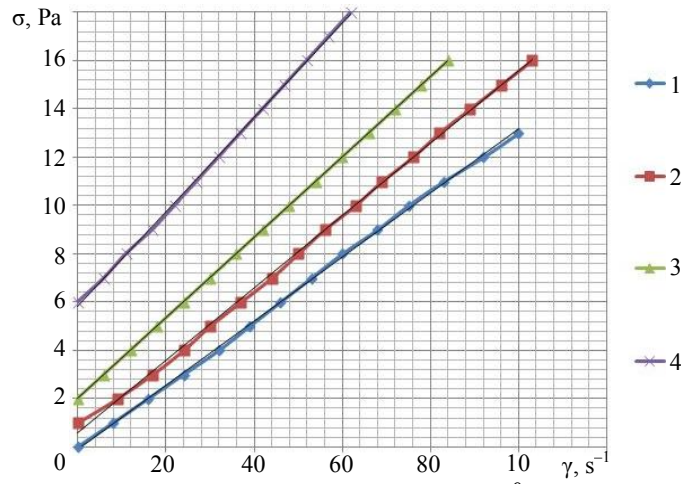


Fig.3. Rheological curves of limonite pulp for mass concentrations 30 % (1); 35 (2); 40 (3); 45 (4)

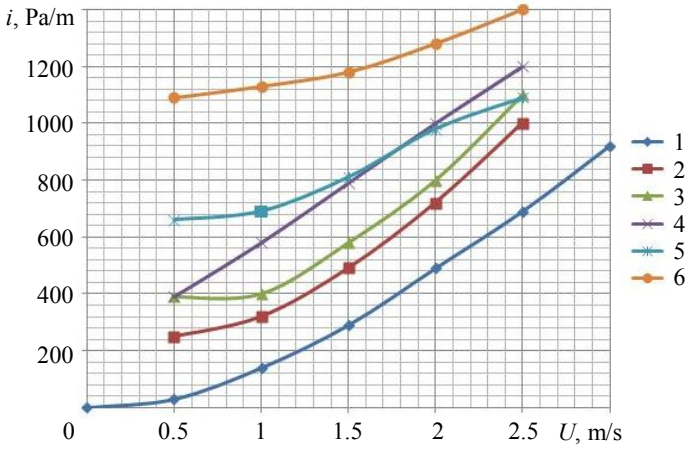


Fig.4. $i(U)$ dependence for limonite pulp flow along the pipeline 100 mm in diameter with mass concentrations:
1 – water; 2 – 25 %; 3 – 30; 4 – 35; 5 – 40; 6 – 45

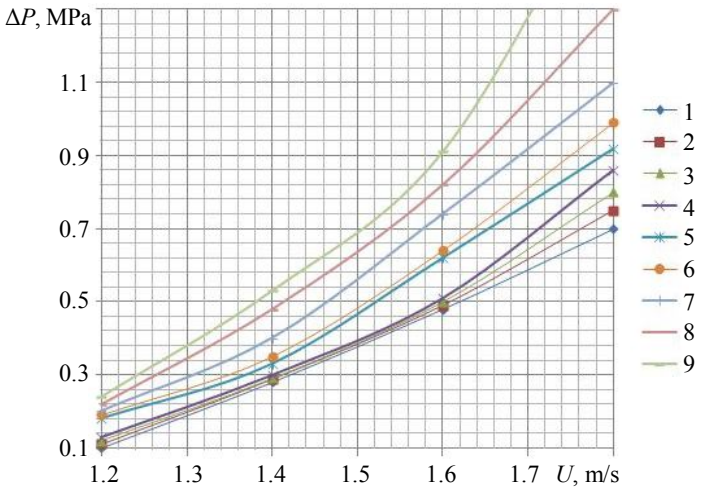


Fig.5. Pressure losses in the pipeline depending on velocity, diameter (D = 0.438; 0.415; 0.366; 0.317; 0.266 m) and pulp concentration (25 % – curves 1-5; 30 % – 6-9)

Basing on performed theoretical and experimental research, a procedure to calculate hydrotransport parameters of limonite pulp has been developed. The idea behind engineering calculation of transportation parameters, taking into account input properties of the fine-grain limonite pulp (production capacity, transportation distance, density), is in estimating operational characteristics of the pipeline and pumps, which guarantee transportation of required volumes of solid material with minimal economic costs and stable performance of the technological system [3].

Calculation procedure is the following. First, the transportation regime of limonite pulp is determined, which is defined by technological specifics of Pedro Soto Alba plant and depends on concentration of the solid ore, the content of which is determined by processing technology and varies from 25 to 48 % in mass [5].

Depending on solid ore concentration, pulp transportation from the processing station to the plant occurs either in structured, or in turbulent regime.

In structured regime, specific pressure losses are defined as follows:

$$i = \frac{\lambda U^2 \rho_{st}}{2D}, \qquad (19)$$

where λ – coefficient of hydraulic resistance; U – velocity of pulp flow; ρ_{st} – pulp density; D – pipeline diameter.

Coefficient of hydraulic resistance λ is calculated using formula (14), depending on Re and I criteria

$$\mathrm{Re} = \frac{UD\rho_{st}}{\eta_{st}}; \quad \mathrm{I} = \frac{\tau_0 D}{\eta_{st} U}. \qquad (20)$$

Rheological parameters τ_0 and η_{st}, obtained with rotary viscosimeter, are estimated using the graph in Fig.5.

In turbulent regime, hydraulic resistance is computed by formulas (15) and (16), taking into account coefficients k_1 and k_2, obtained by experiment.

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Obtained values of specific pressure losses are used to calculate required pump head and to choose its type, providing established parameters. Flow rate of the pulp is calculated and compared to the estimated value [1, 8].

To perform calculations for designed hydrotransportation line Moa-East, a computer program has been developed, aimed at estimating pressure losses ΔP for different pipeline diameters and concentrations. Results of calculations are presented in Fig.6. Graphs in Fig.6 allow to estimate capacity of solid ore production facility depending on the velocity, pipeline diameter and solid mass concentration.

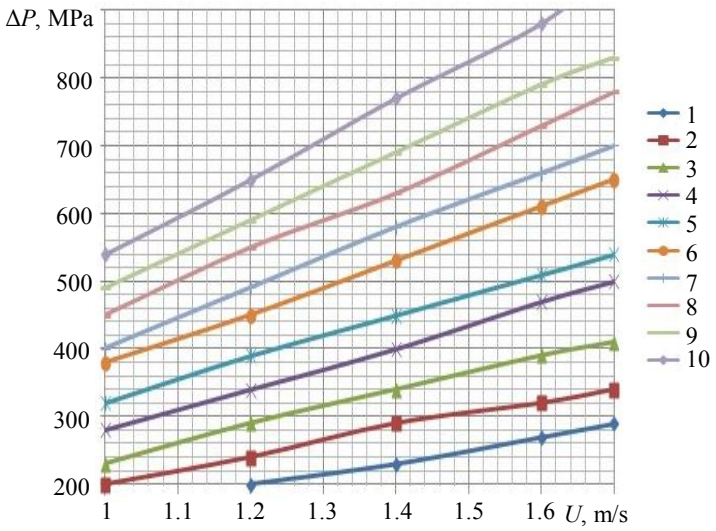


Fig.6. Capacity of solid ore production depending on velocity, diameter and pulp concentration: (25 % – curves 1-5; 30 % – 6-10)

As an alternative option, a combination of gravity and pressurized hydrotransportation is proposed, where the pulp is fed to the final height of the route (58 m) using elevation difference [4, 5]. Hence, the feed station has to be 32 m (2 m as a reserve) higher than the end of the pipeline, i.e. at the level of 90 m. In the initial section of the route, 300 m in length and elevation difference of 33 m, cascading system has to be installed [1]. Slope angle of the chutes should not exceed 1.5 %.

Conclusions

Currently there is no universally accepted, sufficiently justified and experimentally confirmed procedure to calculate hydraulic resistances, associated with viscoplastic pulp flows.

Suggested procedure of calculation, based on Shvedov-Bingham rheological equation, requires relevant adjustments, relying on experimental research.

The main approach to estimating hydraulic resistance is to replace the actual rheological dependency by an empirical formula, close to the experimental flow curve of a specific pulp.

Basing on performed investigations of rheological properties of limonite pulp, a working hypothesis has been proposed, according to which, from the position of concentration and velocity, three zones can be distinguished in the current, characterized by the following flow regimes: structured, transition and turbulent. Basing on this hypothesis, a physical model of limonite fine-grain pulp flow has been developed and its mathematical description prepared.

Performed investigations allowed:

• to establish a dependence in order to estimate coefficient of hydraulic resistance for pulp flow in structured regime;

• to obtain formulas to compute pressure losses for viscoplastic pulp flow in turbulent regime in horizontal pipeline;

• to define the greatest slope angle of pipelines, applicable for limonite pulp transportation, which equals 25 degrees.

Practical recommendations consist in developed procedure to calculate parameters of limonite pulp hydrotransportation facility in turbulent and structured regimes, which allow to obtain better justified and more precise results.

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The paper was accepted for publication on 29 November, 2016.