UDC 622.648.2

ENERGY EFFICIENCY OF HYDRAULIC TRANSPORTATION OF IRON ORE PROCESSING TAILINGS AT KACHKANARSKY MPP

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The article presents analytical calculations of specific pressure losses during hydraulic transportation of slurry tailings from iron ore beneficiation processes at the Kachkanarsky MPP during the storage of processing tailings in the tailings pond. The calculations were performed based on the results of experimental studies of dependence of specific pressure losses on roughness of inner surface of pipelines lined with polyurethane coating. In the process of experimental determination of pipeline polyurethane coatings roughness, it was established that the physical roughness of the coatings is more than four times less than the roughness of steel pipelines, which leads to a decrease in the coefficients of hydraulic resistances included in the design formula for the specific pressure losses - the Darcy-Weisbach formula. The coefficients of relative and equivalent roughnesses for pipelines with and without coating have been calculated. Comparative calculations have shown that the use of polyurethane coatings of hydrotransport pipelines contributes to a decrease in the specific energy during hydraulic transportation of processing tailings of iron ore from Kachkanarsky MPP in 1.5 times. To assess the nature and intensity of changes in the physical roughness of test pipes with polyurethane coating, experiments were performed on the roughness on a laboratory hydraulic bench. The prepared slurry of the iron ore tailings of Kachkanarsky MPP was pumped through a looped pipeline, in the linear part of which three test coated pipes were sequentially installed. Experiments showed that the roughness after running 484 hours on all the samples of the pipelines varies insignificantly. Roughness values are in the range from 0.814 to 0.862 μm. As a result of the processing of experimental data by mathematical statistics, an empirical formula is obtained for calculating the surface roughness of the polyurethane coating surface, depending on the time of operation of pipeline transporting the slurry of the iron ore processing tailings.

***Key words*:** roughness, hydraulic resistance coefficient, equivalent roughness, particle-size composition, hydraulic mixture, specific pressure loss

***How to cite this article*:** Alexandrov V.I., Timukhin S.A., Makharatkin P.N. Energy Efficiency of Hydraulic Transportation of Iron Ore Processing Tailings at Kachkanarsky MPP. Zapiski Gronogo instituta. 2017. Vol. 225, p. 330-337. DOI: 10.18454/PMI.2017.3.330

Introduction. One of the important directions of intensification of mining and ore production, increasing its efficiency and competitiveness in the current market relations is the creation of a powerful transport base capable of significantly increasing the productivity of transport systems while reducing the cost of transportation of mineral raw materials and products of its processing. The development of such a base is connected with the introduction of continuous types of transport, among which the most popular in mining industry has become the hydraulic pipeline transport.

Currently, in the mining and ore production industrial complex there are about 400 pressure hydrotransport systems, the total length of the pipeline which exceeds 1,300 km. These systems annually move more than 1.5 billion tons of various solid bulk materials, mainly tails of mineral raw materials and concentrates processing.

JSC “EVRAZ KGOK” is one of the five largest mining enterprises in Russia. The production capacity of the plant is more than 55 million tons of iron ore per year. The main consumer of EVRAZ KGOK's products is EVRAZ NTMK. EVRAZ KGOK extracts ore from three quarries with its further processing in crushing, mineral processing, agglomeration and lumping shops.

The analysis of hydrotransport systems operation process at mining enterprises shows that the efficiency of using this type of transport does not correspond to its technical capabilities, the work labor input during equipment operation, the abrasive wear of pipelines, the metal consumption and the energy intensity of hydrotransport systems are high.

The specific energy capacity of hydraulic transport depends on the specific pressure losses and the concentration of the solid phase of the slurry [3]:

 DOI: 10.18454/PMI.2017.3.330

$$E = \frac{N}{q_s L} = \frac{\rho_m g I_m}{3.6 \rho_s c_v}, \quad (1)$$

where E – process specific energy intensity, kW·h/(t·km); N – pumps power, kW; q_s – system productivity for solid materials, t/h; L – pipeline length (transportation distance), km; ρ_m – hydraulic mixture density, t/m^3; ρ_s – solid tails density, t/m^3; g – acceleration of gravity, m/s^2; I_m – specific losses of pressure, m wat.st/m; c_v – volumetric concentration of solid particles in hydraulic mixture.

As it can be seen from formula (1), the energy intensity of the transportation process depends mainly on the specific losses of pressure I_m during transportation of the slurry (slurry tailings) through the pipeline and on the value of the solid phase c_v concentration in the transported flow of slurry. Reduction of pressure losses and increase in concentration lead to a decrease in work for pumping a given volume of solid material - milltailings.

It is known that the main energy losses during the pipeline transportation of fluids are spent on overcoming frictional forces of fluid flow on internal surfaces of the pipeline, and depend on the value of the hydraulic resistance coefficient λ, included into the Darcy-Weisbach formula [5],

$$I = \lambda \frac{v^2}{2gD}, \quad (2)$$

where v – fluid flow velocity, m/s; D – pipe diameter, m.

The hydraulic resistance coefficient is a function of relative roughness of pipe walls and Reynolds number [6, 7], defining the fluid flow mode, i.e.

$$\lambda = f(\varepsilon, \mathrm{Re}), \quad (3)$$

where $\varepsilon = \Delta/D$ – relative roughness of pipe walls; Δ – absolute (physical) roughness of pipe walls, μm; $\mathrm{Re} = vD\rho/\mu$ – Reynolds number; ρ – fluid density, kg/m^3; μ – dynamic viscosity coefficient, Pa·s.

It follows from formulas (2) and (3) that by changing the physical roughness of the pipeline walls, it is possible to influence the value of the specific pressure losses during the hydraulic transportation of fluids, including slurries of ore processing tailings.

Hydraulic resistance coefficient and flow patterns. In the laminar fluid flow pattern ($\mathrm{Re} \le 2300$), the coefficient of hydraulic resistance does not depend on the pipe wall roughness, but is determined only by the Reynolds number value according to the Stokes formula [6, 7]

$$\lambda = \frac{64}{\mathrm{Re}}. \quad (4)$$

In the friction zone, characteristic for hydraulically smooth pipes (the height of unevenness is covered by a fluid film), the coefficient of hydraulic resistance also does not depend on the wall roughness. This flow pattern occurs at Reynolds numbers in the range $2300 < \mathrm{Re} \le 100000$. The coefficient λ is calculated by the Blasius formula

$$\lambda = \frac{0.3164}{\mathrm{Re}^{0.25}}. \quad (5)$$

Almost all hydrotransport pipelines operate in modes of transition to turbulent and in turbulent mode, when the value of roughness of the pipeline walls determines the value of hydraulic resistance values [8, 12].

Let us calculate the value of Reynolds number for the conditions of the Kachkanarsky MPP using the following formula

$$\mathrm{Re} = \frac{vD\rho_m}{\mu}. \quad (6)$$

DOI: 10.18454/PMI.2017.3.330

Let us set the following values of quantities: $D = 1000$ mm; $v = 4.8$ m/s; $\rho_m = c_v(\rho_s - 1) + 1 = 1092$ kg/m^3; $\mu = 1.017$ Pa·s.

It is assumed in the calculation that the mass concentration of the processing tailings slurry $c_p = 10$ %, which corresponds to $c_v \cong 3$ %, according to the formula $c_v = c_p \frac{\rho_m}{\rho_s} = 0.1 \cdot \frac{1092}{3300} = 0.033$.

For pipeline $D = 1000$ mm the Reynolds number is

$$\mathrm{Re} = \frac{4.8 \cdot 1.0 \cdot 1092}{1.017 \cdot 10^{-3}} = 5.154 \cdot 10^6.$$

For pipeline $D = 900$ mm, average velocity $v = 4.0$ m/s and the same slurry properties the Reynolds number will be

$$\mathrm{Re} = \frac{4.0 \cdot 0.9 \cdot 1092}{1.017 \cdot 10^{-3}} = 3.865 \cdot 10^6.$$

In fact, we get that the pattern of pulp flow in pipelines that is a developed turbulent one. Under the developed turbulent mode (quadratic friction zone), the coefficient λ does not depend on the Reynolds number, but is determined by the coefficient of relative roughness ε in accordance with the Shifrison formula

$$\lambda = 0.11\varepsilon^{0.25}. \quad (7)$$

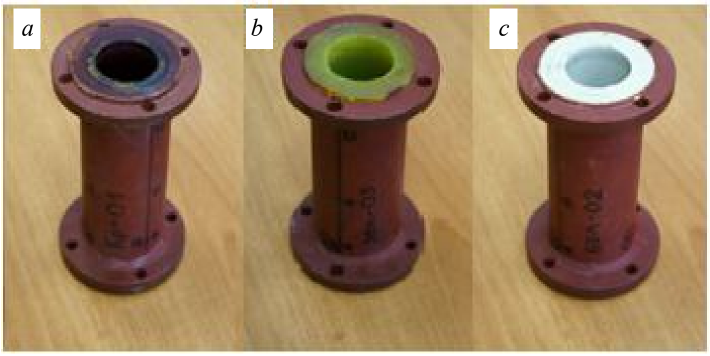


Fig.1. General view of test pipe samples with polyurethane lining: *a* – Shore hardness 83A; *b* – 85A; *c* – 90A

Physical roughness of inner surface of pipelines. At Department of Mining Transport Machines of Saint-Petersburg Mining University there have been conducted test research of roughness of pipelines fitted with polyurethane lining. The lining material is polyurethane with Shore hardness 83A, 85A and 90A (GOST 24621-91). The test pipe samples with lining are shown on Fig.1.

The surface roughness measurements were made using a special SJ-210 instrument. The contact profilometer (roughness meter) is an inductive sensor (detector in the form of a measuring probe) with a diamond needle and support on the measured area [11]. The needle (probe) moves perpendicular to the test surface. The sensor generates pulses passing through the electronic amplifier. The resulting mechanical vibrations of the probe are converted into a digital signal. Processing of several such signals makes it possible to calculate the average value of the parameter - the quantitative characteristic of section roughness from the calculation for a given length.

To do the measurement we have assembled a measuring unit which general view is shown at Fig.2.

Fig.2. General view of measuring unit
1 – profilometer; 2 – PC; 3 – logement; 4 – test samples with polyurethane lining; 5 – a piece of steel pipe (new pipe); 6 – a piece of steel pipe with run in roughness (used pipe)

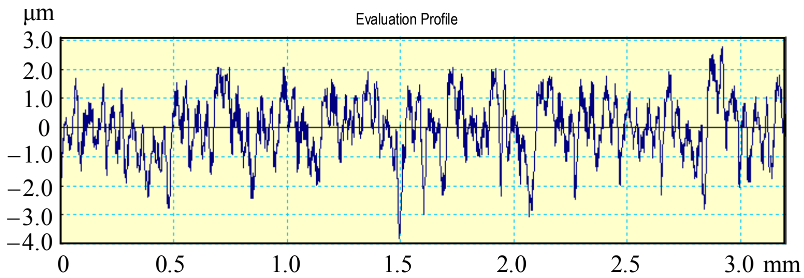
The measurement unit display sample N 1 is given at Fig.3. Measured and average roughness values of test pipe samples with lining are given in Table 1. Similar roughness measurements were performed for pieces of steel pipeline walls – new and used ones (Table 2).

To assess the nature and intensity of changes in the roughness of test pipes with polyurethane coating, experiments on development of roughness on a laboratory hydraulic bench were performed. The prepared slurry of processing tailings of iron ore of Kachkanarsky MPP with solid phase concentration $c_p = 10\ \%$ was pumped through the looped pipeline (Fig. 4), in the linear part of which three samples of pipes with coating were installed sequentially. The total operation time was 484 h.

The hydraulic bench test results are shown in Table 3. From Table 3 it is seen that after working during 484 hours roughness of all test pipe samples changes slightly. The roughness values are within the range from 0.814 to 0.862 μm. As a result of experimental data processing using mathematical statistics, an empirical formula was obtained for calculating the roughness as a function of the pipeline operation time

$$R_a = 0.814 + 9.92 \cdot 10^{-5} T_{op}, \quad (8)$$

where R_a – average roughness of pipe wall, μm; T_{op} – pipeline operation time, h.



Work Name	Sample	Operator	Mitutoyo
Measuring Tool	SurfTest	Comment	Ver2.00

Standard	ISO 1997	N	4
Profile	R	Cut-Off	0.8mm
λs	2.5μm	Filter	GAUSS

Ra	0.799 μm	Rmr(c)2	2.609 %
Rq	1.007 μm	Rdc	0.581 μm
Rz	5.335 μm	Rt	6.557 μm
Rp	2.236 μm	Rz1max	5.868 μm
Rv	3.099 μm	Rk	2.536 μm
Rsk	-0.362	Rpk	0.771 μm
Rku	3.108	Rvk	1.249 μm
Rc	2.713 μm	Mr1	9.078 %
RSm	65.9 μm	Mr2	88.797 %
RDq	0.234	A1	3.50
Rmr	0.109 %	A2	7.00
Rmr(c)1	0.797 %		

Fig.3. Presentation of roughness measurement results: top – spectrogram of rough surface, bottom – a table with roughness values

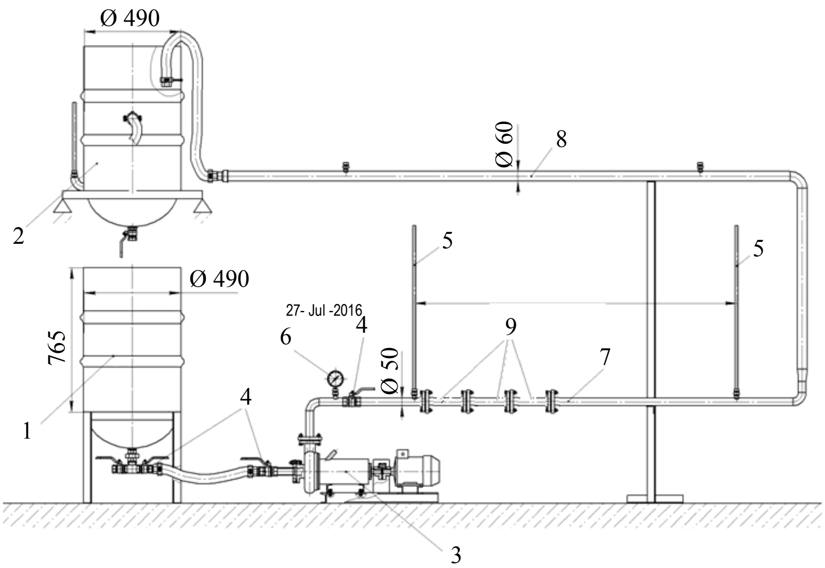


Fig.4. Layout of laboratory test bench

1 – feed tank 100 liters; 2 – measuring tank; 3 – pump CN30/18-U2 with induction motor; 4 – ball valve; 5 – piezometers; 6 – test pressure gauge; 7 – pipeline with internal diameter of 50 mm; 8 – pipeline with internal diameter of 60 mm; 9 – test pipe samples with internal polyurethane coating

Using equation (8) we can forecast developed roughness in time. For example, for time T_{op} = 2000 h (3 months) of continuous operation of hydraulic transportation system the average roughness if internal surface will be R_a = 1.012 μm; for T_{op} = 2000 h (5 months) R_a = 1,211 μm; for T_{op} = 8000 h (about 1 year) R_a = 1,608 μm.

DOI: 10.18454/PMI.2017.3.330

Table 1

Results of roughness measurements of test pipe samples with polyurethane coating

Measurement point	Red sample, hardness 83A			Yellow sample, hardness 85A			Grey sample, hardness 90A		
	Line I	Line II	Line III	Line I	Line II	Line III	Line I	Line II	Line III
A	1.343	0.379	0.54	1.266	0.642	0.564	0.780	0.798	0.636
B	0.73	0.996	0.696	1.389	1.248	0.877	0.799	0.730	0.726
C	0.893	0.57	0.457	0.876	1.039	1.135	0.91	0.554	0.412
R_a	0.988	0.648	0.564	1.177	0.976	0.859	0.830	0.694	0.591
$R_{a(\mathrm{av})} = \Delta$		**0.734**			**1.004**			**0.705**	

Table 2

Measured values of internal surface roughness of steel pipelines

Measurement point	New pipe			Used pipe		
	Line I	Line II	Line III	Line I	Line II	Line III
A	2.749	2.809	2.821	5.147	4.199	3.883
B	4.742	4.883	4.913	4.2	3.964	4.088
C	4.903	4.358	4.306	4.618	5.199	5.199
R_a	4.131	4.016	4.306	4.618	4.454	4.39
$R_{a(\mathrm{av})} = \Delta$		**4.053**			**4.499**	

Table 3

Roughness values of used pipe samples

Test sample with Shore roughness	Average roughness ($R_a \cdot 10^3$) in operation time, h						
	0	4	28	52	148	242	484
83A	0.734	0.815	0.908	0.876	0.764	0.95	0.828
85A	1.004	1.031	0.975	1.063	0.782	0.788	0.822
90A	0.705	0.783	0.872	0.962	0.983	0.854	0.935
Average value	**0.814**	**0.815**	**0.918**	**0.967**	**0.843**	**0.864**	**0.862**

Determination of roughness, coefficients of hydraulic resistance and pressure loss. The method for determining the roughness Δ, taken in hydraulics, takes into account that the natural (geometric $R_a = \Delta$) is always inhomogeneous, the ridges and gaps of roughness have different shapes, locations and sizes. The microrelief of pipe inner walls surface depends on many factors: material, method of pipe production, physicochemical properties of pumped fluid and service life.

Since natural roughness has variable irregular shapes (Fig.5, *a*), to establish in some geometric way the averaged value of the pimples height, which determines the effect of roughness on the loss of pressure, is impossible. That is why roughness parameter is viewed as imputed value, determined with special scale of artificial uniform roughness (Fig.5, *b*).

Such a scale is created with the help of calibrated grains of sand, glued to the smooth surface of the pipe. The set of such pipes for different diameters of grains Δ gives a number of relative roughness Δ/D, in which the λ values are obtained (I.Nikuradze formula) [4, 9, 10]

$$\lambda = \frac{1}{\left(2\lg\frac{\Delta}{D} + 1.14\right)^2}. \quad (9)$$

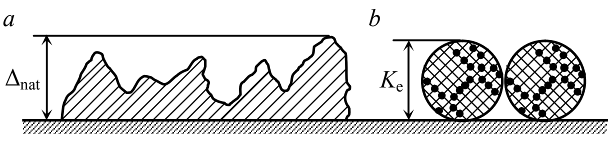


Fig.5. Natural (*a*) and equivalent (*b*) roughness

With the help of a special scale, the absolute roughness is assumed to be equivalent to a roughness, which is the size of sand grains of artificial roughness, which in the quadratic zone is equivalent to the hydraulic resistance of this inhomogeneous surface.

DOI: 10.18454/PMI.2017.3.330

The results of studies [2]of relation between coefficient of equivalent and natural roughness on 13 samples of low and high pressure polyethylene pipes with diameters from 25 to 400 mm, as well as the results of studies performed by G.A.Trukhin (two reinforced concrete collectors with diameters of 1.6 and 1.94 m, allowed to find mathematical relationship in Research and Development Institution VODGEO (eight water lines made of different materials with various diameters from 0.7 to 1.2 m) to define this relation:

$$K_e = 2\Delta^{1.33}. \qquad (10)$$

On the basis of these assumptions, we calculated the value of equivalent roughness coefficient by formula (10), given by operating time of hydrotransport pipeline T_{op} = 1000 h,

$$K_e = 2\cdot\left(0.814 + 9.92\cdot10^{-5}\cdot1000\right)^{1.33} = 1.772\ \mu\text{m}.$$

Thus, the expected value of equivalent roughness for a pipeline with a hardness of polyurethane coating of pipe internal surface in the range of 83A-95A after pipeline operating during T_{op} = 1000 h during transportation of processing tailings slurry of Kachkanarsky MPP with mass concentration of solids about 10 %, will equal K_e = 1.772 µm.

We take the obtained value of equivalent roughness for calculating the coefficient of hydraulic resistance λ and the specific pressure loss I. We determine the coefficient of equivalent roughness for a steel pipeline that was in operation. In accordance with GOST 8.586-1-2005 (ISO 5167-2003), the equivalent roughness for steel pipelines is calculated by the formula

$$K_e = \pi R_a. \qquad (11)$$

For calculation, we use the value of natural roughness of hydraulic transportation pipeline section R_a = 4.49 µm (Table 2),

$$K_e = \pi\cdot4.49 = 14.1\ \mu\text{m}.$$

It can be seen that the values of equivalent roughness for a used steel pipe line significantly exceed the values for a coated pipeline (by almost a factor of seven). Accordingly, the coefficients of hydraulic resistances and the specific pressure losses will be significantly different.

The coefficient of hydraulic resistance, which is a function of relative roughness in the quadratic area of friction (resistance), for a pipe of 1000 mm with an inner polyurethane coating in accordance with the Shifrison formula will be equal to

$$\lambda_l = 0.11\varepsilon^{0.25} = 0.11\left(\frac{K_e}{D}\right)^{0.25} = 0.11\left(\frac{1.772\cdot10^{-3}}{1000}\right)^{0.25} = 0.004.$$

The coefficient of hydraulic resistance for used steel pipe is

$$\lambda_{st} = 0.11\left(\frac{14.1\cdot10^{-3}}{1000}\right)^{0.25} = 0.007.$$

Specific losses of pressure are calculated for the conditions of Kachkanarsky MPP taking into account the new values of hydraulic resistance coefficients λ_l and λ_{st}. For pressure losses in a pipe line coated with a layer of polyurethane with Shore hardness from 83A to 90A,

$$I = I_v + \Delta I_v = \lambda_l\frac{v^2}{2gD} + k_\rho\delta\sqrt[4]{j}\sqrt[3]{c_v^2};$$

$$I = 0.004\frac{4.8^2}{2\cdot9.81\cdot1.0} + 3.3\cdot0.056\cdot\sqrt[4]{0.2}\cdot\sqrt[3]{0.04^2} = 0.0155.$$

In steel pipeline without lining

$$I = I_v + \Delta I_v = \lambda_{st}\frac{v^2}{2gD} + \Delta I;$$

$$I = 0.007\frac{4.8^2}{2\cdot 9.81\cdot 1.0} + 3.3\cdot 0.056\cdot \sqrt[4]{0.2}\cdot \sqrt[3]{0.04^2} = 0.0232.$$

The calculation results for roughness coefficient, hydraulic resistance and specific pressure losses (pipeline D = 1000 mm, operation time T_{op} = 1000 h) are given in Table 4.

Table 4

Calculated results

Pipeline	Indicators			
	Physical roughness Δ, μm	Equivalent roughness K_e, μm	Coefficient of hydraulic resistance λ	Specific pressure loss I, m wat. st./m
Polyurethane coating	0.913	1.772	0.004	0.0155
Steel	4.49	14.1	0.007	0.0232

Conclusion

1. The established values of surface roughness of polyurethane coatings, relative roughness coefficients and calculated values of specific pressure losses confirm the efficiency of using pipelines with a polyurethane internal lining in transportation systems for processing tail slurry.

2. The Shore hardness of polyurethane coating surfaces in the range of values from 83 A to 90 A (experimental coatings) has no practical effect on the intensity of internal coating surface roughness changes.

3. Hydraulic resistances of slurry pipelines during transportation of tail slurry with mass concentration of solid phase of c_p = 10 % is proportional to the ratio of equivalent roughness K_e to pipe diameter according to the formula $\lambda = 0.11\left(\frac{K_e}{D}\right)^{0.25}$. For working diameter of pipeline of 1000 mm when operating in the zone of quadratic friction (developed turbulent mode of hydraulic mixture flow) the hydraulic resistance coefficient in average of 1000 h of continuous operation will not exceed λ_{av} = 0.004.

4. The calculated values of specific pressure loss in pipeline with polyurethane coating with hydraulic transportation of hydraulic mixture of processing tailings with mass concentration of solid phase c_p = 10 % equal to $I_{m\,1}$ = 15.5 m wat. st/km, that is almost 1.5 times lower than in steel pipeline without any coating ($I_{m\,1}$ = 23.2 m wat.st/km).

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The paper was accepted for publication on 6 February, *2017.*