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ESTIMATION OF EFFICIENCY OF HYDROTRANSPORT PIPELINES POLYURETHANE COATING AS COMPARED TO STEEL PIPELINES

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The paper presents analytical calculations of specific pressure loss in hydraulic transport of the Kachkanarsky GOK iron ore processing tailing slurry. The calculations are based on the results of the experimental studies on specific pressure loss dependence upon hydraulic roughness of pipelines internal surface, lined with polyurethane coating. The experiments proved that hydraulic roughness of polyurethane coating is four times smaller than that of steel pipelines, resulting in the decrease of hydraulic resistance coefficients entered into calculating formula of specific pressure loss - the Darcy-Weisbach formula. Relative and equivalent roughness coefficients are calculated for pipelines with polyurethane coating and without it. Comparative calculations show that hydrotransport pipelines polyurethane coating application is conductive to specific energy consumption decrease in hydraulic transport of the Kachkanarsky GOK iron ore processing tailings slurry by the factor of 1.5.

KEY WORDS: roughness, hydraulic resistance coefficient, equivalent roughness, slurry, specific pressure loss.

1. INTRODUCTION

Pressure loss is one of the main parameters of hydraulic transport raw minerals processing, as it actually determines operational energy costs in the hydraulic transport system. Modern trends in productivity growth resulting from the mining enterprise engaging in the processing of large volumes of all ores lead to increasing the load on the hydraulic transport system and tail slurries, and, accordingly, on the tailings storage. The operational system of hydrotransport efficiency can be estimated by energy intensity of the transportation process (Aleksandrov V. I. et al, 2015, 2012).

It is known that the main energy losses arise when the liquid flow rubs against the inner surface of the pipeline. They depend on the value of the coefficient of hydraulic resistance included in the formula for Darcy-Weisbach (Darcy H., 1857).

Hydraulic drag coefficient is a function of the relative pipe wall roughness and Reynolds numbers [Heywood N. et al, 1978, 2003] and determines the fluid flow regime, i.e.

$$\lambda = f(\varepsilon, \mathrm{Re}). \tag{1}$$

At the Kachkanar GOK, industrial testing of high density polyethylene pipelines was carried out. The tests did not show a significant increase in the service life of the slurry pipeline. The outlet pipeline was made of polyethylene pipes installed on the pipeline of the distribution slurry and after a week of work had a through hole made by solid particles.

At the same factory, elbow swivels of technical fluids with internal walls of polyurethane coating were used. Operation of polyurethane coating elbow swivels shows that in this case, the service life is over 10 times longer than steel elbow swivels without polyurethane coating.

From hydraulics it is known that the coefficient of hydraulic resistance does not depend on the roughness of the inner surface of the pipeline and in laminar regime ($\mathrm{Re} \le 2300$) is a function only of the Reynolds number by the Stokes formula or by the Blasius formula for hydraulically smooth pipes. Such regimes are possible with hydraulic transport of highly concentrated fine-dispersed mixtures, when rheological properties appear in the flow of pulp.

In practice all hydrotransport pipelines operate in modes close to turbulent or turbulent ones, when pipe wall roughness determines the hydraulic resistance (Kumar U. et al, 2015; Schmitt D. J., 2004).

In the developed turbulent regime the hydraulic drag coefficient is independent of the Reynolds number, and is determined by the relative roughness coefficient in accordance with the formula Shifrison

$$\lambda = 0.11\varepsilon^{0.25}. \tag{2}$$

2. PHYSICAL ROUGHNESS OF THE INNER SURFACE OF PIPES

Experimental investigations of surface roughness of pipelines with polyurethane coating were carried out in the hydraulic laboratory of St. Petersburg Mining University. The coating material is polyurethane with hardness Shore surface - 83A, 85A and 90A . Experienced coated pipe samples are shown in Fig. 1.

Surface roughness of the coating is measured using a special device SJ-210. Contact profilometer (surface roughness meter) is an inductive sensor (detector in the form of a probe) with a diamond needle and based on the measured area. The needle (probe) moves perpendicular to the inspected surface. The sensor generates pulses that pass through an electronic amplifier. The emerging mechanical oscillations of the probe are converted into a digital signal. Statistical analysis of several of these signals allows us to calculate the average value of the parameter - quantitative characteristics of the plot irregularities based on a certain length.

The test installation was assembled to carry out the measurements, the general form of which is shown in Fig. 2.

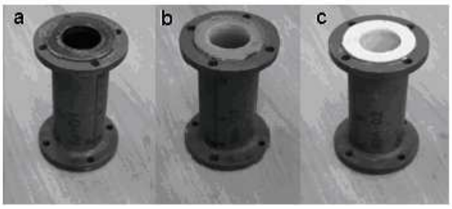

Fig. 1. Prototypes pipes with polyurethane coating: a - hardness Shore 83A; b - hardness of 85A; c- hardness 90A

Fig. 2. Measuring setup: 1 – profilometer, 2 – PC, 3 – lodgment, 4 – pipes with a polyurethane coating, 5, 6 - element of steel pipes

Measurements of the surface roughness of prototype pipes were made according to the three coating forming on the inner length of 120 mm, with a consequent bend in the samples of 120°, and three line samples on steel pipes. The total number of measurements at each measurement sample was equal to 27. The measured values were averaged. The arithmetic mean value was taken as the absolute surface roughness . The results of each measurement were displayed on the computer screen in the form of a spectrogram and characteristic table values.

The absolute (physical) roughness of prototype pipelines are given in Table. 1, where Ra means arithmetic average.

Table 1

Surface roughness of prototype pipes coated with polyurethane

The measuring point	hardness 83A			hardness 85A			hardness 90A		
	Line I	Line II	Line III	Line I	Line II	Line III	Line I	Line II	Line III
	The measured values of roughness (Ra) , μm								
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
$R_a = \Delta$	**0.734**			**1.004**			**0.705**		

Similar measurements were performed for roughness of wall elements of steel pipe - new and used, see Table. 2.

To assess the nature and intensity of changes of roughness of the prototype pipes with polyurethane coating, experiments on an operating time of roughness were performed on a laboratory hydraulic installation.

In the linear part of the pipeline three prototypes of pipes with a polyurethane coating were installed. Slurry tailings of Kachkanarsky GOK with a weight solids content of 10% were poured into a supply tank of the installation with a capacity of 100 liters. The slurry was pumped through a pipeline with an internal diameter of 50 mm using the centrifugal pump CP30/18. Pump flow was controlled by a frequency converter. Pump capacity at the maximum motor speed was 45 m^3/h. From the pipeline the slurry got into the measuring tank, which was used to determine the flow rate, and then poured into the supply tank.

Table 2

Measured values of the inner surface of steel pipe roughness

The measuring point	New pipe			Pipe with a run-roughness (used pipe)		
	Line I	Line II	Line III	Line I	Line II	Line III
	The measured values of roughness (Ra) , μm					
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= Δ	**4.053**			**4.499**		

The practice of hydrotransport operation shows that the steady value of the surface roughness of steel pipe occurs approximately after one month of continuous operation of the pipeline, which corresponds to 720 hours. The average flow rate in the current pipeline ($D = 1000$ mm) from the pumping station №1 of Kachkanarsky GOK (according to the company) is 4.8 m/s. These data were used to determine the total flow time of the slurry tailings through line pipes and prototypes until a steady inner surface roughness was established. The estimated time was 484 hours. To determine the nature and dynamics of the roughness of polyurethane coatings prototype pipes, total run time of the pump unit was divided into several time intervals: 4, 24, 24, 96, 96, 240 (hours). The pump was turned off after each time interval, the experiment pipe was dismantled, and the accumulated roughness was measured. The values of accumulated roughness of the prototype pipe samples are shown in Table. 3.

Table 3

Values of accumulated roughness of prototype pipe samples

Sample pipe with a Shore hardness	The average surface roughness ($Ra \times 10^3$ $\mu м$) for the operating 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
The average value	**0.814**	**0.815**	**0.918**	**0.967**	**0.843**	**0.864**	**0.862**

From the data of Table. 3 it follows that the roughness after 484 hours of working time for all samples of the prototype pipeline varies slightly. The roughness values are in the range from 0.814 to 0.862 μm. After processing the experimental data by methods of mathematical statistics the empirical formula for calculating the roughness, depending on the time of operation of the pipeline was obtained:

$$Ra = 0.814 + 9.92 \cdot 10^{-5} T_{op} . \qquad (3)$$

where Ra is the average roughness of the pipe wall, μm; T_{op} is working time of the pipeline, h.

Using equation (3), the value of the accumulated roughness can be calculated as a function of the pipeline working time. For example, at time $T_{op} = 2000$ h (3 months) of continuous operation of hydrotransport system, the average roughness of the inner surface is equal to $Ra = 1.012$ μm; for $T_{op} = 4000$ h (5 months) $\rightarrow$ $Ra = 1.211$ μm; $T_{op} = 8000$ h (approximately 1 year) $\rightarrow$ $Ra = 1.608$ μm.

3. CALCULATING ROUGHNESS, COEFFICIENTS OF HYDRAULIC RESISTANCE AND LOSSES OF PRESSURE

The method of calculating roughness used in hydraulics takes into account that the natural (geometric $R_a = \Delta$) is always heterogeneous: peaks and troughs have different shapes, sizes and location. Surface microrelief of an internal pipe wall depends on many factors including the material, method of manufacturing, and physical and chemical properties of the fluid and lifetime. Since the natural roughness has multiple irregular shape (Fig.3a), it is impossible to calculate the averaged value of the height of hillocks which determine the effect of roughness on the pressure loss by any geometrical methods. Therefore, the parameter of roughness is considered as a conditional value determined by a special scale of artificial homogeneous roughness (Fig. 3b).

a) b)

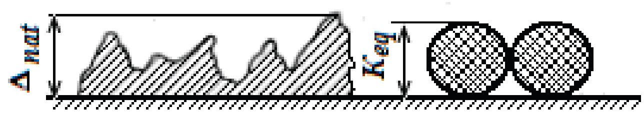

Fig.3. Natural (a) and equivalent roughness (b)

The scale of roughness is constructed with the help of calibrated grains of sand, glued to the smooth surface of the pipe. A set of such pipes with different grain diameters gives a number of values of relative roughness, in the function of which values are obtained (J. Nikuradze's formula) [Nikuradse J., 1932]

$$\lambda = \frac{1}{\left(2\lg\frac{\Delta}{D} + 1.14\right)^2}. \tag{4}$$

By means of such a scale, the absolute roughness is taken to be its equivalent value, that is, the size of the grains of artificial roughness sand, which in the quadratic region of friction with respect to the hydraulic resistance is equivalent to this inhomogeneous surface.

The results of studies (Dobromyslov A. I., 2004) of the relationship between the coefficient of equivalent and natural roughness on 13 samples of low-pressure and high-pressure polyethylene pipes with diameters from 25 to 400 mm, as well as the results of studies carried out by G.A. Trukhin (two reinforced concrete collectors with diameters of 1.6 and 1.94 m) VNII VODGEO (eight water pipes from various materials with diameters from 0.7 to 1.2 m) made it possible to establish a mathematical dependence for determining this connection:

$$K_{eq} = 2 \cdot \Delta^{1.33}, \quad (5)$$

where $\Delta = R_a$ - the natural roughness, μm.

Based on these assumptions, we calculate the value of the equivalent roughness coefficient by the formula (5), given by the operating time of the hydrotransport pipeline $T_{op} = 1000$ hours. We'll have

$$K_{eq} = 2 \cdot \left(0.814 + 9.92 \cdot 10^{-5} \cdot 1000\right)^{1.33} = 1.772 \text{ μm.}$$

Thus, the expected value of the equivalent roughness for a pipeline with a polyurethane coating on the inner surface of the pipe with hardness in the range 83A-95A, after the operating $T_{op} = 1000$ hours, when pumping the slurry of the Kachkanarsky GOK processing tailings with a mass concentration of solid about 10%, is equal to $K_{eq} = 1.772$ μm.

We assume the obtained value of the equivalent roughness to calculate the coefficient of hydraulic resistance λ and the specific head loss I.

We determine the coefficient of equivalent roughness for a steel pipe 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

$$K_{eq} = \pi R_a. \quad (6)$$

For calculation K_{eq}, we use the value of the natural roughness of the hydrotransport pipeline element ($R_a = 4.49$ μm), Table 2.

$$K_{eq} = \pi \cdot 4.49 = 14.1 \text{ μm.}$$

It can be seen that the equivalent roughness values for a steel pipeline are significantly higher than the values for a coated pipeline (almost eight times). Accordingly, the coefficients of hydraulic resistance and the specific head loss will be significantly different.

The coefficient of hydraulic resistance, which is a function of the relative roughness in the quadratic area of friction (resistance), for a pipe of 1000 mm with an inner polyurethane coating (λ_{coat}), according to Shifison's formula, will be equal to:

$$\lambda_{coat} = 0.11 \cdot \varepsilon^{0.25} = 0.11\left(\frac{K_{eq}}{D}\right)^{0.25} = 0{,}11 \cdot \left(\frac{1.772 \cdot 10^{-3}}{1000}\right)^{0.25} = 0.004 \cdot$$

The coefficient of hydraulic resistance for a steel run-in pipeline (λ_{st}), will be equal to

$$\lambda_{st} = 0.11\left(\frac{14.1 \cdot 10^{-3}}{1000}\right)^{0.25} = 0.007 \cdot$$

Specific head losses are calculated for the conditions of the Kachkanarsky GOK, taking into account the new values of the coefficients of hydraulic resistance λ_{coat} and λ_{st}. We will have for head losses in the pipeline lined with a layer of polyurethane with a hardness of Shore from 83A to 90A:

$$I = I_в + \Delta I_в = \lambda_{фут} \frac{v^2}{2gD} + k_\rho \delta \sqrt[4]{j} \cdot \sqrt[3]{c_{об}^2};$$

$$I = 0.004 \frac{4.8^2}{2 \cdot 9.81 \cdot 1.0} + 3.3 \cdot 0.056 \cdot \sqrt[4]{0.2} \cdot \sqrt[3]{0.04^2} = 0.0155 \cdot$$

In the steel pipeline (without coating):

$$I = I_0 + \Delta I_0 = \lambda_{st} \frac{v^2}{2gD} + \Delta I_0;$$

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

The results of calculations of the roughness coefficients, hydraulic resistances and specific head losses are given in Table. 4.

Table 4

Calculated values of coefficients of roughness, hydraulic resistances and specific head losses (pipeline $D = 1000$ mm)

Pipeline	Parameters			
	Natural roughness (Δ), μm	Equivalent roughness (K_{eq}), μm	Coefficient of hydraulic resistance (λ)	Specific head loss (I), m w.c./m
Polyurethane coating	0.913	1.772	0.004	0.0155
Steel	4.49	14.1	0.007	0.0232

4. CONCLUSION

1. The established values of the surface roughness of polyurethane coatings, the values of the relative roughness coefficients and the calculated values of specific head losses confirm the efficiency of using pipelines with a polyurethane coating of the pipeline inner surface in hydrotransport system of tail pulp.
2. Hardness of surface of polyurethane coatings in the Shore scale from 83A to 90A (experimental coatings) does not have a practical effect on the intensity of the change in the roughness of the coating surface.
3. Hydraulic drag coefficient in pipeline during the transportation of tail pulp with a mass concentration of solid phase c_p = 10% is proportional to the ratio of equivalent roughness (K_{eq}) to the diameter of the pipeline by the formula $\lambda = 0.11\left(\frac{K_{eq}}{D}\right)^{0.25}$. For the working diameter of the pipeline D = 1000 mm, when working in the zone of quadratic friction (developed turbulent flow regime of the slurry), the hydraulic resistance coefficient on average for 1000 hours of continuous operation will not exceed λ = 0.004.
4. Calculated values of specific head losses in the pipeline with polyurethane coating for hydraulic transport of the slurry of the concentration tailings with a solid concentration

of 10% is I_{coat} = 15.5 m w.c./km, which is almost 1.5 times less than in the uncoated steel pipeline (I = 23.2 m w.c./km).

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