Estimation of efficiency of hydrotransport pipelines polyurethane coating application in comparison with steel pipelines

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Abstract. 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 by the factor of four smaller than that of steel pipelines, resulting in a 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 a specific energy consumption decrease in hydraulic transport of the Kachkanarsky GOC iron ore processing tailings slurry by the factor of 1.5. The experiments were performed on a laboratory hydraulic test rig with a view to estimate the character and rate of physical roughness change in pipe samples with polyurethane coating. The experiments showed that during the following 484 hours of operation, roughness changed in all pipe samples inappreciably. As a result of processing of the experimental data by the mathematical statistics methods, an empirical formula was obtained for the calculation of operating roughness of polyurethane coating surface, depending on the pipeline operating duration with iron ore processing tailings slurry.

1. Introduction
Specific pressure loss is one of the main parameters of hydraulic transport raw minerals processing, as actually determined operational energy costs in the hydraulic transport system. Modern trends in productivity growth as a result of the mining enterprise engaging in the processing of large volumes of all ores are responsible for increasing the load on the hydraulic transport system and tail slurries - on the tailings concentrator, respectively. The operational system of hydrotransport efficiency can be estimated at the cost of a particular energy transportation process [1, 2]

$$E = \frac{N}{q \cdot L} = \frac{\rho_h g \bar{I}_h}{3.6 \rho_s c_v}, \text{ kW} \cdot \text{h/(t} \cdot \text{km}),$$

(1)

where $N$ - power pumping units, KW; $q_s$ - performance of the system in solid tailings t/h; $L$ - the transport distance, km; $\rho_h$, $\rho_s$ - the density of the slurry and solid particles, respectively, t/m$^3$; $I_h$ - pressure loss along the pipe, m/m; $c_v$ - the volume concentration of solids in the slurry.
The formula shows that the decrease in the pressure loss reduces energy density of the hydrotransport system, i.e. reduces the power consumption for driving pumps.

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: [3]

\[ I = \lambda \frac{v^2}{2gD}, \]  

(2)

where \( v \) - the flow velocity, m/s; \( D \) - the diameter of pipeline, m.

A hydraulic drag coefficient is a function of the relative pipe wall roughness and Reynolds numbers [4, 5] and determines the fluid flow regime, i.e.

\[ \lambda = f(\varepsilon, \text{Re}), \]  

(3)

where \( \varepsilon = \frac{\Delta}{D} \) - relative roughness of the pipe wall; \( \Delta \) - absolute (physical) roughness of the pipe wall, m; \( \text{Re} = \frac{vD}{\mu} \) - Reynolds number; \( \rho \) - liquid density, kg/m³; \( \mu \) - dynamic viscosity Pa·s.

At the Kachkanarskoye 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 during the working week, when the through hole is worn by solid particles.

At the same factory, angular rotations of technical fluids were used, lined with internal walls of polyurethane coating. Operation with a polyurethane coating turns shows that in this case, the service life of more than 10 times longer than the angular rotations of steel without a polyurethane coating.

2. Hydraulic resistance coefficient and flow regime

In laminar fluid flow regime (\( \text{Re} \leq 2300 \)) coefficient of hydraulic resistance does not depend on the roughness of the walls, but is determined only by the value of the Reynolds number for the Stokes formula [4, 5]

\[ \lambda = \frac{64}{\text{Re}}. \]  

(4)

In the friction zone typical for hydraulically smooth tubes (where the height roughness is coated with liquid film), the coefficient of hydraulic resistance does not depend on the roughness of the walls. Such flow regime occurs at Reynolds numbers in a range of \( 2300 < \text{Re} \leq 100000 \). This ratio is calculated by the formula of Blasius:

\[ \lambda = \frac{0.3164}{\text{Re}^{0.25}}. \]  

(5)

In practice, all hydrotransport pipelines operate in the mode of transition to turbulent regimes, when the pipe wall roughness value determines the hydraulic resistance value [6, 7].

Let us calculate the value of the Reynolds number for the conditions of Kachkanar MPC by formula

\[ \text{Re} = \frac{vD\rho_h}{\mu}, \]  

(6)

Let us set the following values of the basic parameters: \( D = 1000 \) mm; \( v = 4.8 \) m/s; \( \rho_h = c_s (\rho_s - 1) + 1 = 0.033 (3.3 - 1) + 1 = 1092 \) kg/m³; \( \mu = 1.017 \times 10^{-3} \) Pa·s. In the calculation it is assumed that the mass concentration is equal to the tailings slurry \( c_p = 10\% \), which corresponds to \( c_s \geq 3\% \) by the formula
For a 1000 mm pipe, the Reynolds number is:
\[
Re = \frac{4.8 \cdot 1.0 \cdot 10^9}{1.017 \cdot 10^3} = 5.154 \cdot 10^6.
\]

For a 900 mm pipeline and the average velocity of pulp \( v = 4.0 \) m/s and similar parameters, the Reynolds number is equal to:
\[
Re = \frac{4.0 \cdot 0.9 \cdot 10^9}{1.017 \cdot 10^3} = 3.865 \cdot 10^6.
\]

In fact, the authors find that the pulp flow regime in pipes is a developed turbulent one. When the regime is developed into turbulent (i.e. square area of friction), the coefficient does not depend on the Reynolds number but is determined by the relative roughness coefficient in accordance with the Shifrison formula:
\[
\lambda = 0.11 \varepsilon^{0.25}.
\]  

3. Physical roughness of the inner surface of pipelines

In the laboratory of the department of mining transport machinery of St. Petersburg Mining University, the authors carried out experimental studies of surface roughness of pipelines covered with polyurethane coating. The coating material was polyurethane with Shore hardness of surface of 83A, 85A and 90A \[8\]. The coated pipe prototypes are shown in Figure 1.

![Pipe prototypes with polyurethane coating](image)

**Figure 1.** A general view of the pipe prototypes with polyurethane coating: a - red color, Shore hardness 83A; b - yellow color, Shore hardness 85A; c - gray color, Shore hardness 90A

The roughness of the surface of the coating was measured using a special device SJ-210. The contact profilometer (surface roughness meter) is an inductive sensor (detector in the form of a probe) with a diamond needle, and it is based on the measured area \[9\]. The needle (probe) moves perpendicularly to the inspected surface. The sensor generates impulses that pass through the electronic amplifier. The emerging mechanical oscillations of the probe are converted into digital signals. The statistical analysis of several of these signals enable us to calculate the average value of the parameter, i.e. the quantitative characteristic of the plot irregularities per certain length.

The test setup assembled for the measurements is shown in Figure 2.
Figure 2. A general view of the measurement setup: 1 - profilometer, 2 – PC, 3 - lodgment, 4 - prototypes with polyurethane coating, 5 – an element of a steel pipe (a new pipe), 6 – an element of a steel pipe with a run-in roughness (a used pipe)

Measurements of the surface roughness of the prototype pipes were made for three samples of polyethylene pipes 120 mm long with different types of inner coating and three samples of steel pipes. A total of 27 measurements were made for each sample. The measured values were averaged. The arithmetic mean value was taken as the absolute surface roughness Δ. The results of each measurement were displayed on the computer screen in the form of a spectrogram and characteristic table values. Example №1 shows the measurements of Figure 3.
Figure 3. Surface roughness measurement results. Top: a spectrogram of surface irregularities; bottom: a table of roughness parameters values

The mean values of the measured roughness values of pipeline prototypes are given in Table 1. Similar measurements were performed for elements of new and used steel pipes, see Table 2.

To assess the nature and intensity of changes in the roughness of the pipe prototypes with polyurethane coating, experiments on acquiring run-in roughness were performed using a laboratory hydraulic installation, Figure 3.

Three prototypes of pipes with polyurethane coating were installed on the linear part of the pipeline. Slurry tailings from Kachkanarsky GOK with a weight solids content of 10% were poured into a supply tank of 100 liter capacity. The slurry was pumped through a pipeline with an internal diameter of 50 mm using centrifugal pump CP30/18. The pump flow was controlled with a frequency converter. The maximum pump capacity was 45 m³/h. From the pipeline, the slurry got into the measuring tank, which was used to determine the flow rate, and then it was poured into the supply tank.

Table 1. Results of measuring the surface roughness of pipe prototypes coated with polyurethane

| The measuring point | hardness 83A | hardness 85A | hardness 90A |
|---------------------|--------------|--------------|--------------|
| Line 1              | 1.343        | 0.379        | 0.54         |
| Line 2              | 0.73         | 0.996        | 0.696        |
| Line 3              | 0.893        | 0.57         | 0.457        |
| Measured values of roughness (Ra), μm |
| Ra                  | 0.988        | 0.648        | 0.564        |
| Rδ                  | 0.976        | 0.976        | 0.859        |
| Rm                  | 0.734        | 1.004        | 0.705        |

Table 2. The measured values of the inner surface roughness of steel pipes

| The measuring point | A new pipe | A pipe with run-in roughness (a used pipe) |
|---------------------|------------|-------------------------------------------|
| Line 1              | 1.343      | 0.379                                     |
| Line 2              | 0.73       | 0.996                                    |
| Line 3              | 0.893      | 0.57                                     |
| Measured values of roughness (Ra), μm |
It is known from the hydrotransportation practice that the constant value of the surface roughness of a steel pipe can be obtained approximately after one month of continuous operation of the pipeline, which is 720 hours. The average flow rate in the current pipeline (1000 mm) from pumping station №1 of Kachkanarsky MCC (according to the company) is 4.8 m/s. The estimated time was 484 hours. To determine the nature and dynamics of the roughness of polyurethane coatings of prototype pipes, the total run time of the pump unit was divided into several time intervals: 4, 24, 24, 96, 96, 240 (hours). The results of experiments on the pilot hydraulic stand are given in Table 3.

| Prototype pipe with Shore hardness | Average surface roughness \( (Ra \times 10^3 \, \mu m) \) for the operating time, h |
|-----------------------------------|-------------------------------------------------|
| 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

It follows from the data that after 484 hours of operating time the roughness for all used pipeline prototypes varies slightly. The roughness values are in the range from 0.814 to 0.862 μm. By processing the experimental data using methods of mathematical statistics, the empirical formula for calculating the roughness depending on the time of operation of the pipeline was obtained:

\[
Ra = 0.814 + 9.92 \times 10^{-3} T_{op} .
\]  

(8)

where \( Ra \) is the average roughness of the pipe wall, \( \mu m \); \( T_{op} \) is the time of operation of the pipeline, h. According to equation (8), the roughness accumulated with time can be predicted. For example, with time \( T_{op} = 2000h \) (3 months) of continuous operation of the hydrotransport system, the average roughness of the inner surface is equal to \( Ra = 1.012 \, \mu m \); for \( T_{op} = 4000h \) (5 months) \( \rightarrow Ra = 1.211 \, \mu m \); \( T_{op} = 8000h \) (approximately 1 year) \( \rightarrow Ra = 1.608 \, \mu m \).
4. Determination of roughness, coefficients of hydraulic resistance and pressure losses

The method of determining the roughness used in hydraulics takes into account the fact that natural roughness (geometric $R_n = A$) is always heterogeneous, i.e. its peaks and troughs have different shapes, sizes and location. The surface microrelief of an internal pipe wall depends on many factors including material, a manufacturing method, physical and chemical properties of the fluid, and lifetime. Since the natural roughness has multiple irregular shapes (Figure 5a), it is impossible to determine by any geometrical method the averaged value of the height of the hillocks which affect the pressure loss. Therefore, the parameter of roughness is considered as a conditional value determined by a special scale of artificial homogeneous roughness (Figure 5b).

![Figure 5](image)

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

This scale is constructed using calibrated grains of sand, which are 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 (I. Nikuradze's formula) [10-12]

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

With the help of such 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 [13] of the relationship between the 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 carried out by G.A. Trukhin (two reinforced concrete collectors with diameters of 1.6 and 1.94 m) at VODGEO Institute (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:

$$K_{eq} = 2 \cdot (1.33^{\frac{\Delta}{1.772}}), \quad \text{(10)}$$

where $\Delta = R_n$ is the natural roughness, $\mu m$.

Based on these assumptions, let us calculate the value of the equivalent roughness coefficient using formula (10), assuming that the operating time of the hydrotransport pipeline $T_{op} = 1000$ hours. Then

$$K_{eq} = 2 \cdot \left(0.814 \cdot 9.92 \cdot 10^{-5} \cdot 1000\right)^{\frac{1}{1.33}} = 1.772 \mu m.$$

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

Let us assume the obtained value of the equivalent roughness to calculate the coefficient of hydraulic resistance $\lambda$ and the specific head loss $I$.

Let us 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

$$K_{eq} = 2 \cdot \left(0.814 \cdot 9.92 \cdot 10^{-5} \cdot 1000\right)^{\frac{1}{1.33}} = 1.772 \mu m.$$
\[ K_{eq} = \pi R_u. \]  

(11)

To calculate \( K_{eq} \) let us use the value of the natural roughness of the hydrotransport pipeline element \( R_u = 4.49 \mu m \), Table 2.

\[ K_{eq} = \pi \cdot 4.49 = 14.1 \mu m \]

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 \( (\lambda_{coat}) \), according to Shifison's formula, will be equal to:

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

The coefficient of hydraulic resistance for a used steel pipeline \( (\lambda_{st}) \), will be equal to:

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

Specific head losses are calculated for the conditions of Kachkanarsky GOK, taking into account the new values of the coefficients of hydraulic resistance \( \lambda_{coat} \) and \( \lambda_{st} \). The resulting head losses in the pipeline lined with a layer of polyurethane with Shore hardness from 83A to 90A will be equal to:

\[ I = I_0 + \Delta I_0 + \frac{\lambda_{st}}{2gD} \frac{v^2}{\Delta I_0} + k_{\mu} \delta \sqrt{\frac{f}{D}} \cdot \sqrt{\frac{c}{c_{00}}} ; \]

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

In an uncoated steel pipeline,

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

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

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

| Pipeline             | Natural roughness (\( \Delta \)), \( \mu m \) | Equivalent roughness (\( K_{eq} \)), \( \mu m \) | Coefficient of hydraulic resistance (\( \lambda \)), | 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                                         |

5. Conclusion
1. The established values of the surface roughness of polyurethane coatings, the values of 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 the hydrotransport system of tail pulp.
2. The hardness of the 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 resistance in a 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 for the average of 1000 hours of continuous operation will not exceed $\lambda = 0.004$.
4. The calculated values of the 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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