Assessment of the flow performance of oil pipelines using the operation discipline monitoring data

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ABSTRACT

Using the example of the oil pipeline operation data analysis, it is shown that the proposed comparison criterion, the performance index of the oil pipeline segment – according to the readings of the pressure gauges at the inlet/outlet of the oil pumping station and at the end of the technological segment of the oil pipeline. Justification of the flow performance index

Energy performance of the oil pipeline as a flow system shall be rationally determined the ratio of useful work to the total energy entering the system from the outside. The classical representation of the energy balance in hydraulics is the Bernoulli equation [17]:

\[ z_1 + \frac{P_1}{\rho g} + \frac{v_1^2}{2g} + H_1 = z_2 + \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + H_2 + \sum \Delta \varepsilon, \]

where subscripts «b» and «e» characterize the parameters of the upstream and downstream oil pipeline segment, respectively.

\[ \sum \Delta \varepsilon = \sum \Delta z + \sum \Delta \psi = \sum \Delta h, \]

 Justiﬁcation of the ﬂow performance index

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ABSTRACT

The article presents a method of quantitative assessment of the oil transportation efficiency through the trunk pipelines’ segments, considering the flow performance of the line section. In accordance with the methodology, the assessment of the oil pipelines’ energy performance parameters is performed according to the data recorded by built-in tools of supervisory control and data acquisition (SCADA) system, including:

- efficiency factor of the oil pumping station – according to readings of pressure gauges installed at the pump station inlet and in the discharge header;
- control factor of the automated pressure control system (APCS) – according to the readings of the pressure gauges installed in the discharge header and in the pumping station outlet line;
- flow performance of the oil pipeline segment – according to the readings of the pressure gauges at the inlet/outlet of the oil pumping station and at the end of the technological segment of the oil pipeline.

Using the example of the oil pipeline operation data analysis, it is shown that the proposed comparison criterion, the performance factor of the technological segment, enables to determine all the traditionally used criteria for assessing the actual operating conditions of the trunk oil pipelines, to identify the characteristic features of each mode, to compare the operation parameters of the pipelines with various diameters and designs.

Key words: Main oil pipeline, energy performance, efficiency factor, performance factor, energy saving, process optimization, flow performance, energy efficiency factor, performance factor, energy saving, process optimization, flow performance.

INTRODUCTION

Energy saving and improving energy performance of trunk oil pipelines are the priority tasks for oil transport industry. More than half of the operating costs in the Transneft system are energy costs, 85% of these costs accrue to the electric power consumption by trunk and booster pipeline pump stations [1].

The tangible result of the company’s implementation of the Energy Saving Program in the period 2012-2015 was saving of 840,404,000 KWh (2.872 mln. RUB), which became possible mainly due to the optimization of pipelines’ operational practices [2]. According to the results of 2017, the specific electric power consumption for oil transportation decreased by 0.59% in annual equivalent, for petroleum products – by 0.82%, and energy savings amounted to 356 mlm. RUB [3].

As part of the topic-based year “2018 – Year of energy saving”, Transneft took several actions, while the most significant area of energy saving was the optimization of the oil pumping process [2, 4].

The development and justification of technological methods to reduce power consumption and improve energy performance in pipeline transport of oil and petroleum products was covered in the works to such distinguished scientists as V. G. Shukhov, L. S. Lebedin, V. I. Chermin, S. V. Yablokon, P. I. Tuganov, V. F. Novoselov, L. S. Abramson, I. A. Chepurin, V. E. Gubin, V. N. Stepanygin, V. M. Lutie [5–13] et al. Nevertheless, the energy saving potential is far from exhausted [14], and the work on identifying reserves for further reduction of energy consumption shall be continued. In 2015, the International Association of Oil Transporters (IAOT) [15] established a permanent expert group on energy performance to share best practice in energy-saving technologies and conduct benchmark studies of energy performance. The results of studies at 20 process segments in 2017 showed that the implementation of measures to improve the energy performance in oil transportation enabled to reduce an average specific electric power consumption by 3.5% compared to the previous year [16].

To establish the methodological base for assessing the oil trunk pipeline operation performance, it is appropriate to develop the tools for condition monitoring in line sections of pipeline’s process segments. The purpose of this article is to substantiate the methodological base of the comparative assessment of energy performance of the oil pipeline’s process segment considering the flow performance of its line section. The assessment is based on the pumping data recorded by built-in tools of SCADA, that can identify:

- efficiency factor of oil pumping station – according to readings of pressure gauges installed at the pump station inlet (P_i) and in the discharge header (P_d);
- control factor of APCS – according to the readings of the pressure gauges installed in the discharge header (P_d) and in the pumping station outlet line (P_p);
- flow performance of the oil pipeline segment – according to the readings of the pressure gauges at the inlet/outlet of the oil pumping station and at the end of the technological segment of the oil pipeline.

Justification of the flow performance index

Energy performance of the oil pipeline as a flow system shall be rationally determined the ratio of useful work to the total energy entering the system from the outside. The classical representation of the energy balance in hydraulics is the Bernoulli equation [17]:

\[ \frac{z_i + \frac{v_i^2}{2g} + \frac{P_i}{\rho g} + h_i}{z_f + \frac{v_f^2}{2g} + \frac{P_f}{\rho g} + h_f} = \frac{\Delta \zeta}{ \rho g} \]

where \( \zeta \) - discharge coefficient; \( \Delta \zeta \) - the difference in elevations between the ends of the process segment, m;

\[ \sum (z_i - z_f) = H \] - the sum of energy losses by friction along the entire length of the process segment, m;

\[ \sum (h_i - h_f) = \eta \] - the total head of the oil pumping station defined as the sum of the differences in discharge pressure (downstream the pressure controller) and intake pressure of each pumping station, measured in meters of the pumped oil column.

Velocity heads difference \( \Delta \zeta = \sum (z_i - z_f) / \rho g \) is equal to zero in the pipeline of constant diameter and negligible for pipelines of variable cross-section [17].

Coming back from theoretical studies into a practical field, we define the flow performance of the pipeline segment as the ratio of useful work, estimated by the required head, to the hydraulic energy spent for planned task, as defined within the process segment using the sum of actual heads of oil pumping station, operating “from pump to pump”:

\[ \eta = \frac{h_{sp} - Mg}{H_{pp} - \Delta \zeta + \frac{P_{pp} - P_{sp}}{\rho g}} \]

(2)
To assess the energy effect of the tank farm hookup, it is necessary to record the differential pressure ($\Delta P_{\text{in}}$) at the pumps intake while filling the tank and pumping the product out of it. In addition, the electricity consumed by the process pumps in the tank farm piping shall be included in the consideration. In absolute terms, additional energy losses in the mode of pumping via the tank can be estimated through the differential pressure at the first oil pumping station intake ($\Delta P_{\text{in}}$) during oil filling and pumping-out:

$$\Delta P_{\text{in}} = \frac{\rho_{\text{in}} g \Delta H}{\rho \cdot \rho_{\text{in}}}$$

where $\rho_{\text{in}}$ - amount of oil transferred through the tank, kg;
3.6·106 kWh/kg - unit conversion factor from J to kWh.

For one turnover of oil in the PBC-20000 tank, up to 2700 kWh is consumed. Additional energy costs for filling/emptying the tank are not explicitly included in the calculation of the process segment performance, as tank farms are usually located between segments.

Performance factor of the trunk line process segment

To determine the efficiency factor of the pumping station, we will use the criterion of the process segment's energy performance [18, 19], which considers the energy consumption of hooked-up pumping units operating “from pump to pump”:

$$W_{\text{in}} = \sum H_{\text{in}} M_{\text{in}} + \sum \left( \frac{P_{\text{in}} - P_{\text{out}}}{P_{\text{in}}} \right) M_{\text{in}}$$

where $W_{\text{in}}$ - energy consumption for pumping $j$ amount of oil $M$ per hour according to the pipeline operational discipline monitoring data, J.

The efficiency factor of the pumping stations in the process segment can be estimated by formula (3):

$$\eta_{\text{ERP}} = \frac{\sum \left( P_{\text{in}} - P_{\text{out}} \right) M_{\text{in}}}{3.6 \times 10^6 \sum \Delta P_{\text{in}}}$$

Regarding the option to monitor the operational parameters of pumping using the monitoring and supervisory control system, the control factor of APCS can be defined as the ratio of the hydraulic energy of the flow upstream and downstream the pressure control valve:

$$\eta_{\text{a}} = \frac{\sum \left( P_{\text{in}} - P_{\text{out}} \right) M_{\text{in}}}{\sum \left( P_{\text{in}} - P_{\text{out}} \right) M_{\text{in}}}$$

Thus, having established all components, we can calculate the performance factor of the trunk pipeline process segment:

$$\eta_{\text{ac}} = \eta_{\text{ERP}} \eta_{\text{a}}$$

(5)

Methodology for calculating efficiency factors of individual pumping units and of the entire pumping station are given in the DFGC Transnet standards [20, 21].

One shall note that the use of the calculated value of energy losses by friction in the numerator of the first term (2) enables to consider all the variety of design solutions of the process segment. Methods of friction losses calculation in pipelines with loopings, inserts, discharging and boosting taps, tees, check valves, gate valves and other components - local drag are given in standards [20, 21] and guidelines [9, 13, 17].

Moreover, the proposed methodology enables to assess the operational performance of the pipeline process segment with anti-turbulence additive injected, using as reference the values the estimated hydraulic losses in (2) considering the decrease of the friction factor [20, 21].

To estimate the first term, we will accept as “useful” work of the fluid friction forces the calculated energy losses due to friction according to the equation of L. S. Lehzen [6]. According to design standards [4],

$$h_{\text{fr}} = h_{\text{fr}} = \frac{\Delta P_{\text{in}}}{\rho g}$$

(7)

where $h_{\text{fr}}$ - the sum of hydraulic losses along the length of the oil pipeline process segment and in local drag zones, m;

$\beta$ - coefficients of L. S. Lehzen equation;
$
u$ - oil kinematic viscosity, m$^2$/s;
$D$ - inner diameter of the pipeline, m;
$L_{\text{eq}}$ - equivalent length of the process segment with local drag zones, m.

The more points are in the group, the more often this scheme of the fluid friction forces is to be taken as true. Thus, having established all components, we can calculate the performance factor of the trunk pipeline process segment:

$$\eta_{\text{ac}} = \frac{\sum \left( P_{\text{in}} - P_{\text{out}} \right) M_{\text{in}}}{3.6 \times 10^6 \sum \Delta P_{\text{in}}}$$

Using (8) the total head of the oil pumping station can be calculated:

$$H_{\text{pump}} = \sum \left( P_{\text{in}} - P_{\text{out}} \right) M_{\text{in}}$$

(9)

where $\Delta P_{\text{in}}$ - the sum of hydraulic losses along the length of the oil pipeline process segment and in local drag zones, m;

$\beta$ - coefficients of L. S. Lehzen equation;
$\nu$ - oil kinematic viscosity, m$^2$/s;
$D$ - inner diameter of the pipeline, m;
$L_{\text{eq}}$ - equivalent length of the process segment with local drag zones, m.

For comparison, the solid red line marks a reference level – the sum of hydraulic losses along the length of the oil pipeline process segment and in local drag zones, m.

Table 1. Recommended coefficients $\beta$ and $m$ [17]

| Flow pattern | Area of use | $\beta$ | $m$ |
|--------------|-------------|--------|-----|
| Laminar      | Re < 2040   | 4.15   | 1   |
| Transient    | 2040 < Re < 2800 | 1.25  | 0.10-0.6 |
| Turbulent    | Re > 2800   | 0.25   | 0.123 |
| Mixed friction | Re < Re Ref  | 0.016640.15 | 0.123 |

Table 1. Recommended coefficients $\beta$ and $m$ [17]

Discussion

A common practice of adapting results of process calculations to the actual indicators according to the SCADA data is the change in the flow cross-section of the pipe. However, the position of mobile slugs in the laid pipeline and their flow drag depend on the pumping flow rate, on the properties of the transported fluids and on the history of operation modes switching. Therefore, the errors of process calculations, adapted to a fixed effective flow section (diameter), have a significant scatter depending on the loading of the pipeline segment.

Using the flow performance indicator, one can easily estimate the correction to the pipe flow cross-section diameter:

$$q_{\text{corr}} = \frac{D_{\text{nom}} - D_{\text{nom}}}{D_{\text{nom}}} = 1 - 0.1 \eta_{\text{nom}} = 0.936..0.017.$$

Table 1. Recommended coefficients $\beta$ and $m$ [17]

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In the example shown in Fig. 1, the diameter corrections for various pipeline operation modes vary widely – from 1.7% to 5.6% of the design value.

A much smaller error of calculations can be obtained by applying the coefficients $\beta$ and $m$ in the Lehzen equation as adaptive parameters.

Linear regression by points of process modes on the plot

Physically, the difference in head, when hooking up the same pumping units is explained by the presence of mobile water and gas slugs in the segment, located along the route at the topography bends. Additional flow drag changes over time due to the migration of slugs and depends on the amount of accumulated water and gas. Studies of pipeline segments with water and gas slugs are given in papers [11, 22–25].
where \( M \) - the amount of pumped oil according to the pipeline operational discipline monitoring data, kg; 
\( \rho_{ps} \) - pressure at the end and the beginning of the process segment (with subscripts e and b, accordingly).

To assess the energy effect of the tank farm hookup, it is necessary to record the differential pressure \( \Delta P_{ps}^{w} \) at the pumps intake while filling the tank and pumping the product out of it. In addition, the electricity consumed by the process pumps in the tank farm piping shall be included in the consideration.

In absolute terms, additional energy losses in the mode of pumping via the tank can be estimated through the differential pressure at the first oil pumping station intake \( \Delta P_{ps}^{w} \) during oil filling and pumping-out:

\[
\Delta P_{ps}^{w} = \frac{M_{ps}}{\rho_{ps} \cdot V_{ps}^{w}}
\]

where \( M_{ps} \) - amount of oil transferred through the tank, kg;
\( \rho_{ps} \) - density of the pumped oil, kg/m³;
\( V_{ps}^{w} \) - unit conversion factor from m³ to M³.

For one turnover of oil in the PBC-20000 tank, up to 2700 kWh is consumed. Additional energy costs for filling/emptying the tank are not explicitly included in the calculation of the process segment performance, as tank farms are usually located between segments.

**Performance factor of the trunk line process segment**

To determine the efficiency factor of the pumping station, we will use the criterion of the process segment's energy performance [18, 19], which considers the energy consumption of hooked-up pumping units operating "from pump to pump":

\[
W_{ps} = \sum \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot L_{ps},
\]

where \( W_{ps} \) - energy consumption for pumping \( m \) amount of oil \( M_{ps} \) per hour according to the pipeline operational discipline monitoring data, J/h.

\[
\sum \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot L_{ps} = \sum \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot \frac{L}{m} \cdot \frac{L_{ps}}{L}
\]

where \( L_{ps} \) - the sum of hydraulic losses along the length of the oil pipeline process segment and in local drag zones, m; 
\( \beta, \eta \) - coefficients of L. S. Leibenzon equation;
\( \nu \) - oil kinematic viscosity, m²/s;
\( D \) - inner diameter of the pipeline, m;
\( L_{ps} \) - equivalent length of the process segment with local drag zones, m.

The efficiency factor of the pumping stations in the process segment can be estimated by formula (3):

\[
\eta_{ps} = \frac{\sum \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot L_{ps}}{3 \cdot 10^{6} \cdot \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot \frac{L}{m} \cdot \frac{L_{ps}}{L}}
\]

Regarding the option to monitor the operational parameters of pumping using the monitoring and supervisory control system, the control factor of APCSs can be defined as the ratio of the hydraulic energy of the flow upstream and downstream the pressure control valve:

\[
\eta_{nc} = \frac{\sum \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot \frac{L}{m} \cdot \frac{L_{ps}}{L}}{3 \cdot 10^{6} \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot L_{ps}}
\]

Thus, having established all components, we can calculate the performance factor of the trunk pump line process segment:

\[
\eta_{ps} = \eta_{nc} \cdot \eta_{lnc} \cdot \eta_{tnc}
\]

Methodology for calculating efficiency factors of individual pumping units and of the entire pumping station are given in the PJSC Transneft standards [20].

One shall note that the use of the calculated value of energy losses by friction in the numerator of the first term (2) enables to consider all the variety of design solutions of the process segment. Methods of friction losses calculation in pipelines with loops, insertions, discharging and boosting taps, tee’s, check valves, gate valves and other components – local drags are given in standards [20] and guidelines [9, 13, 17].

Moreover, the proposed methodology enables to assess the operational performance of the pipeline process segment with anti-turbulence additive injected, using as reference the values the estimated hydraulic losses in (2) considering the decrease of the friction factor [20, 21].

To estimate the first term, we will accept as "useful" work of the fluid friction forces the calculated energy losses due to friction according to the equation of L. S. Leibenzon [6].

According to design standards [4,5]:

\[
h_{ps} = h_{ps} = \frac{\beta \cdot \nu \cdot D^{2} \cdot L_{ps}}{D^{2}}
\]

where \( h_{ps} \) - hydraulic losses along the length of the oil pipeline process segment and in local drag zones, m; 
\( \beta, \eta \) - coefficients of L. S. Leibenzon equation; 
\( \nu \) - oil kinematic viscosity, m²/s; 
\( D \) - inner diameter of the pipeline, m; 
\( L_{ps} \) - equivalent length of the process segment with local drag zones, m.

We convert the L. S. Leibenzon equation as follows:

\[
h_{ps} = \frac{\beta \cdot \nu \cdot D^{2} \cdot L_{ps}}{D^{2}} = \beta \cdot \frac{\nu \cdot D^{2} \cdot L_{ps}}{D^{2}} = \beta \cdot \nu \cdot D^{2} \cdot L_{ps}
\]

Thus, having established all components, we can calculate the efficiency factor of the trunk pump line process segment:

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\eta_{ps} = \eta_{nc} \cdot \eta_{lnc} \cdot \eta_{tnc}
\]

The efficiency factor of the pumping stations in the process segment can be estimated by formula (3):

\[
\eta_{ps} = \frac{\sum \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot L_{ps}}{3 \cdot 10^{6} \cdot \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot \frac{L}{m} \cdot \frac{L_{ps}}{L}}
\]

**Table 1. Recommended coefficients \( \beta \) and \( m \) [17]**

| Flow pattern | Area of use | \( \beta \) | \( m \) |
|--------------|-------------|-----------|-------|
| Laminar      | Re > 2040   | 4.15      | 1     |
| Turbulent    | 2040 < Re < 2800 | 1.25 | 10.6 |
| Mixed friction | Re < ReRef | 0.25      |       |
| Square-law friction | Re > ReRef | 0.016640.15 | 0.123 |
| Hydrodynamically smooth pipes | 2800 < Re < Ref | 0.0246 |       |

Physically, the difference in head, when hooking up the same pumping units is explained by the presence of mobile water and gas slugs in the segment, located along the route at the topography bends. Additional flow drag changes over time due to the migration of slugs and depends on the amount of accumulated water and gas. Studies of pipeline segments with water and gas slugs are given in papers [11, 22–25].

**Discussion**

A common practice of adapting results of process calculations to the actual indicators according to the SCADA data is the change in the flow cross-section of the pipe. However, the position of mobile slugs in the laid pipeline and their flow drag depend on the pumping flow rate, on the properties of the transported fluids and on the history of operation modes switching. Therefore, the errors of process calculations, adapted to a fixed effective flow section (diameter), have a significant scatter depending on the loading of the pipeline segment.

Using the flow performance indicator, one can easily estimate the correction to the pipe flow cross-section diameter:

\[
\delta = \frac{D_{ps}}{D_{ps}^e} = \left( \frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \right) \cdot L_{ps} \cdot \beta \cdot m \cdot (\text{Re}) = \text{const.}
\]

In the example shown in Fig. 1, the diameter corrections for various pipeline operation modes vary widely – from 1.7% to 5.6% of the design value.

A much smaller error of calculations can be obtained by applying the coefficients \( \beta \) and \( m \) in the Leibenzon equation as adaptive parameters.

Linear regression by points of process modes on the plot

\[
\frac{\rho_{ps} \cdot V_{ps}^{w}}{M_{ps}} \cdot D_{ps}^e \cdot \beta \cdot m \cdot \text{Re} = \text{const.}
\]

(Fig. 1): \( y = 0.3664 x - 0.1537 \) gives the value of parameters: 

\( \beta = 0.3664 \)
The discrepancy between the process calculations and the actual operating parameters in this case will be due only to the scatter of points relative to the median line:

$$O\left( D - D_{op} \right) \sim -\ln \eta_{op} = 0.034 \ldots 0.022. \ (11)$$

To further improve the accuracy of process calculations, it is necessary to apply the methodology of multiphase fluid flow in the topographic pipeline, considering the accumulation and migration of water and gas slugs [26], the justification of which is beyond the scope of this article.

Let us return to the justification of the method of evaluating the operation performance coefficients of the oil pipeline process segment.

Each point on the plot can be easily estimated by the parameter "flow performance". According to the definition of the first term in the flow performance formula (2):

$$\eta_{op} = \frac{H_{op} - H_{i}}{H_{op}} \frac{g D^{2}}{Q^{2} L} \left( \frac{g H_{i} D^{2}}{Q^{2} L} \right)$$

or, in logarithmic coordinates:

$$\ln \eta_{op} = \ln \frac{g D^{2}}{Q^{2} L} - m \ln (g H_{i} D^{2}) - 1.4212 - 0.250 \ln \left( \frac{Q}{Q_{D}} \right); \quad m = \frac{\ln \eta_{op} - 1.4212 - 0.250 \ln \left( \frac{Q}{Q_{D}} \right)}{-1.4212 - 0.250 \ln \left( \frac{Q}{Q_{D}} \right)}\ (12)$$

The first term in the right part of the expression (12) is the ordinate of the theoretical characteristic of the oil pipeline [7,8] with coefficients from the Table 1.

If we use the notation of the right part of the equation (12) in the vertical coordinate $$Y = \ln \left( \frac{g D^{2}}{Q^{2} L} \right)$$ then we obtain a graphical representation of the first term in the expression for the flow performance $$\eta_{op}$$: the vertical distance between the actual mode marked by the point on the plot and the theoretical (or statistically average) characteristic of the pipeline shown on the red line ($$\Delta Y$$ in Fig. 1).

Thus, a graphical representation of the actual operating modes in the form of a plot (Fig. 1) gives a qualitative assessment of each operating mode of the process segment of the oil trunk pipeline: the higher is the point above the reference line, the lower is the flow performance.

The analytical formula for calculating the first term in an expression for the flow performance $$\eta_{op}$$ in the operating mode of the process segment of the oil pipeline can be obtained from (12), using the coefficients $$\beta$$ and $$m$$ from the Leibenzon discipline monitoring in January 2018 in coordinates $$\eta_{op}, M$$ (Table 1).

An alternative way of determining the flow performance of the pipeline segment without graphical plots:

$$\ln \eta_{op} = \frac{\beta}{H_{op}} \frac{Q_{D}^{2} \left( g H_{i} D^{2} \right)}{Q^{2} L}$$

where the coefficients $$\beta$$ and $$m$$ should be taken from the Table 1 according to the hydraulic friction zone in the pipeline.

The average monthly performance indicators of the Yaroslavl – Moscow oil pipeline operation in January 2018 were:

- $$\eta_{op} = 99,9 \%$$;
- $$\eta_{flow} = 56,7 \%$$;
- $$\eta_{pump} = 86,1 \%$$.

Thus, having a methodological basis for calculating all components of the performance factor of the trunk pipeline process segment – $$\eta_{op}$$ we obtain a convenient and informative tool for analyzing the operation performance of the trunk pipeline’s process segment: plotting the trend of efficiency factors in the coordinates $$\left( \eta_{op}, M \right)$$, where $$M$$ – total amount of oil pumped during the reporting period, $$M_{d}$$ – current hourly amount of oil pumped taken from the plot of pipeline operational discipline monitoring as cumulative total within the reporting period (Fig. 2).

To control the transition from one mode to another, performance factors plots can be conveniently combined with the mass flow rate $$G$$.

In the first decade of January, the Yaroslavl – Moscow oil pipeline operated in a constant mode. There is clearly the trend of a proportional decrease in flow performance and pumping flow rate – by 1.5%. In the second decade of the month, the modes were switched – from 1300 t/h to 880 t/h and 1070 t/h. At each switching, spikes in the performance curves are observed, apparently caused by recording wave processes in the SCADA system. However, the trend to reduce performance and throughput capacity is maintained.

Two factors are superimposed: 1) the less is the flow rate of the process segment, the lower is the flow performance (group of points 1 in Fig. 1), 2) the mode performance decreases with time, as in the first decade of January. The described trend continues until the segment of the oil pipeline is "swung" at increased flow rate. Such dynamics of performance indicators (first, flow performance) can be explained by considering the regularities of accumulation of water and gas slugs in particular segments of the oil pipeline.

Reduction of oil pipelines throughput capacity due to flow drag of water, gas-air slugs and asphaltene-resin-wax deposits significantly depends on the topography of the area and uniformity of distribution of mobile and stationary slugs along the line pipe. According to V. I. Golosovker [27], such a decrease can reach 30 %, according to the results of other studies [26, 28] – 12…25 %.

Analyzing changes of performance indicators according to the plot of pipeline operational discipline monitoring data for the oil pipeline Yaroslavl – Moscow in the coordinates $$\left( \eta_{op}, M \right)$$ (Fig. 2), each parameter can be estimated in hourly dynamics to investigate the reasons of local decrease of this or that indicator. However, for generalization, it is convenient to operate with monthly average values (Table 2), which are defined as the area under the corresponding efficiency factor curve (Fig. 2):

$$\eta_{area} = \sum \frac{M}{M} \cdot \left( 1 - \frac{M}{M_{o}} \right)$$

The average monthly performance indicators of the Yaroslavl – Moscow oil pipeline operation in January 2018 were:

- $$\eta_{op} = 86,1 \%$$;
- $$\eta_{flow} = 99,9 \%$$;
- $$\eta_{pump} = 65,9 \%$$;
- $$\eta_{area} = 56,7 \%$$.
with the result:
\[ \eta_{\text{eval}} = \exp \left( \frac{\beta h}{Q^2} \right) \]

Thus, a graphical representation of the actual operating modes of the process segment of the oil pipeline: the higher is the point above the reference line, the closer are the process calculations and the theoretical equation (Table 1). For example, for the oil pipeline Yaroslavl – Moscow, zones of hydraulically smooth pipes are:
- point group I: 0.837…0.869;
- point group II: 0.845…0.896;
- point group III: 0.857…0.917;
- point group IV: 0.857…0.947.

If we use the notation of the right part of the equation (12) in the vertical coordinate 
\[ Y = \ln \left( \frac{\beta h}{Q^2} \right) \] then we obtain a graphical representation of the first term in the expression for the flow performance \( \eta_{\text{eval}} \). The vertical distance between the actual mode marked by the point on the plot and the theoretical (or statistically average) characteristic of the pipeline shown on the red line (5V in Fig. 1):
\[ \eta_{\text{eval}} = \exp \left( \frac{\beta h}{Q^2} \right) \]

Thus, having a methodological basis for calculating all components of the performance factor of the trunk pipeline process segment – \( \eta_{\text{eval}} \) – we obtain a convenient and informative tool for analyzing the operating performance of the trunk pipeline’s process segment: plotting the trend of efficiency factors in the coordinates \( M_{\text{ps}} \) vs. \( M_{\text{pc}} \) where \( M_{\text{ps}} \) – total amount of oil pumped during the reporting period, \( M_{\text{pc}} \) – current hourly amount of oil pumped taken from the plot of pipeline operational discipline monitoring as cumulative total within the reporting period (Fig. 2).

To control the transition from one mode to another, performance factors plots can be conveniently combined with the mass flow rate \( G \).

In the first decade of January, the Yaroslavl – Moscow oil pipeline operated in a constant mode. There is clearly the trend of a proportional decrease in flow performance and pumping flow rate – by 1.5%. In the second decade of the month, the modes were switched – from 1500 t/h to 880 t/h and 1070 t/h. At each switching, spikes in the performance curves are observed, apparently caused by recording wave processes in the SCADA system. However, the trend to reduce performance and throughput capacity is maintained.

Two factors are superimposed: 1) the less is the flow rate of the process segment, the lower is the flow performance (group of points I in Fig. 1), 2) the mode performance decreases with time, as in the first decade of January. The described trend continues until the segment of the oil pipeline is "swung" at increased flow rate. Such dynamics of performance indicators (first, flow performance) can be explained by considering the regularities of accumulation of water and gas slugs in particular segments of the oil pipeline.

Reduction of oil pipelines throughput capacity due to flow drag of water, gas-air slugs and asphaltene-resin-wax deposits significantly depends on the topography of the area and uniformity of distribution of mobile and stationary slugs along the line pipe. According to V. I. Goloubovskiy [27], such a decrease can reach 30%, according to the results of other studies [26, 28] – 12–25%.

Analyzing changes of performance indicators according to the plot of pipeline operational discipline monitoring data for the oil pipeline Yaroslavl – Moscow in the coordinates \( \eta_{\text{eval}} = \left[ \frac{M_{\text{ps}}}{M_{\text{pc}}} \right] \) (Fig. 2), each parameter can be estimated in hourly dynamics to investigate the reasons of local decrease of this or that indicator. However, for generalization, it is convenient to operate with monthly average values (Table 2), which are defined as the area under the corresponding efficiency factor curve (Fig. 2):
\[ \eta_{\text{eval}} = \sum \frac{M_{\text{ps}}}{M_{\text{pc}}} \]

The average monthly performance indicators of the Yaroslavl – Moscow oil pipeline operation in January 2018 were:
- \( \eta_{\text{eval}} = 86.1 \% \);
- \( \eta_{\text{eval}} = 99.9 \% \).

The ratio of the difference in elevation at the beginning and at the end of the route to the sum of the heads of all pumping stations in the process segment for pipelines in the plain terrain, as a rule, does not exceed 10%. For the Yaroslavl – Moscow oil pipeline, this value is 5.8%.

Thus, having a methodological basis for calculating all components of the performance factor of the trunk pipeline process segment – \( \eta_{\text{eval}} \) we obtain a convenient and informative tool for analyzing the operating performance of the trunk pipeline’s process segment: plotting the trend of efficiency factors in the coordinates \( M_{\text{ps}} \) vs. \( M_{\text{pc}} \) where \( M_{\text{ps}} \) – total amount of oil pumped during the reporting period, \( M_{\text{pc}} \) – current hourly amount of oil pumped taken from the plot of pipeline operational discipline monitoring as cumulative total within the reporting period (Fig. 2).
The throughput capacity of the Yaroslavl – Moscow oil pipeline in January 2018 decreased by 4.9% - 10.5% during the month in the considered example, at average – by 8.9 % compared to the design parameters: the month in the considered example, at average – by 8.9%.

The estimation of specific energy consumption for oil pumping comes down to the ratio of the design required head to the values of the required head, in turn, calculated using the consumed for oil pumping through the pipeline and determined according to the pipeline operational discipline monitoring methodology.

The analysis of flow performance using the components of the performance indicator of the oil trunk pipeline’s process segment has a solid theoretical background and is a tool to comparative assessment of the operation performance of pipelines with various diameters and designs.

The proposed approach enables to consider all the variety of design solutions for the oil trunk pipeline’s process segment. It is suggested that the revealed scatter of the required heads (Fig. 1), when hooking-up one and the same pumping units, as well as periodic decrease of performance indicators in the constant pipeline operating modes (Fig. 2) is explained by the presence of mobile water and gas slugs located in particular segments along the pipeline route at the topography bends, and their migration with the oil flow.

The proposed performance factor of the oil pipeline’s process segment enables determining the traditionally used criteria for assessing the actual operating modes of oil trunk pipelines.

Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

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Findings

1. The analysis of flow performance using the components of the performance indicator of the oil trunk pipeline’s process segment has a solid theoretical background and is a tool to comparative assessment of the operation performance of pipelines with various diameters and designs.

2. Level of ηp details – pumping station efficiency factor, APCS control factor, flow performance of the line section of the oil trunk pipeline’s process segment is determined by options to record pumping parameters using in-built SCADA tools. Expanding the list of recorded parameters by pressure at the inlet/outlet of the oil pumping station will make it possible to monitor the performance indicators of the trunk and booster pumps within the framework of the proposed methodology.

3. Representation of actual operation modes of the trunk pipeline in coordinates enables to make the integrated analysis of their flow performance, to compare them and to cross-check against design values, to define features of each mode.

4. It is suggested that the revealed scatter of the required heads (Fig. 1), when hooking-up one and the same pumping units, as well as periodic decrease of performance indicators in the constant pipeline operating modes (Fig. 2) is explained by the presence of mobile water and gas slugs located in particular segments along the pipeline route at the topography bends, and their migration with the oil flow.

5. The proposed performance factor of the oil pipeline’s process segment enables determining the traditionally used criteria for assessing the actual operating modes of oil trunk pipelines.

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The throughput capacity of the Yamal – Moscow – Omsk sector of the oil pipeline in January 2018 decreased by 4.9% - 10.5% during the month in the considered example, at average – by 8.9% (Table 2).

Average monthly operation performance indicators of PJSC Transneft oil pipelines’ process segments.

Table 2.

| Facility                                      | Performance indicator | Adaptive parameters | %      | %      | %      | kWh/km·thous.t | s²/m | – |
|-----------------------------------------------|-----------------------|---------------------|--------|--------|--------|----------------|------|---|
| Yakorudel – Moscow, DN 700                    | ηPS                   | –                   | 56.7   | 86.3   | 99.9   | 65.9           | 6.83 | 0.0084 | 0.3664 |
| Yuzhny Balyk – Togli, DN 1200                 | ηFlow                 | –                   | 54.7   | 86.4   | 98.3   | 64.4           | 9.132| 0.0094 | 0.4074 |
| Krasnoleninsk – Shaim-Konda, DN 800           | ηPc                   | –                   | 46.3   | 91.6   | –      | 50.6           | 5.204| 0.0101 | 0.3150 |
| Omlik – Anahoro-Sudzhensk, DN 700             | ηOPS                  | –                   | 61.7   | 94.9   | 99.1   | 65.6           | 6.116| 0.00757| 0.3300 |
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