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Peculiarities of the operation of the oil pipeline in the process of its cleaning from paraffin deposition

M.D. Serediuk
Department Oil and Gas Pipelines and Storage Facilities, Institute of Petroleum Engineering,
Ivano-Frankivsk National Technical University of Oil and Gas,
15, Karpatska str., Ivano-Frankivsk, Ukraine
Corresponding e-mail address: serediukm@gmail.com
ORCID identifier: https://orcid.org/0000-0002-6874-6947

ABSTRACT

Purpose: Improving the technology of cleaning the inner surface of the main oil pipelines from paraffin deposition by specifying the hydrodynamic parameters of the movement of the cleaning device in the cavity of the pipeline, by more accurate prediction of the time of its approach to the final point of purification.

Design/methodology/approach: Performing theoretical researches and application of mathematical modelling methods in order to establish the regularities of the cleaning device movement in the oil pipeline.

Findings: Regularities of changes in the capacity of the pipeline, the speed of the cleaning process, the specific energy consumption for oil transportation as a function of the linear coordinates of the place and time of the cleaning device movement in the pipeline were established.

Research limitations/implications: The next stage of research is to establish the influence of the characteristics of the viscoplastic fluid of the paraffin plug on the additional resistance and the mode of the cleaning device movement in the pipeline.

Practical implications: It was developed the method that allows predicting the capacity and energy efficiency of the pipeline operation for each point in time of the process of cleaning from paraffin deposition.

Originality/value: The originality of the method is the taking into account the additional hydraulic resistance of the paraffin plug and the available energy resources of oil pumping stations on the hydrodynamic process of moving the cleaning device in the oil pipeline.

Keywords: Pipeline capacity, Mechanical cleaning method, Cleaning device, Hydrodynamic calculation, Plug formed by paraffin deposition, Viscoplastic fluid, Specific electricity consumption

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MANUFACTURING AND PROCESSING

1. Introduction

During the operation of main oil pipelines, pumping paraffin oil, paraffin deposition are formed on the inner surface of the pipe walls. This reduces the live cross section of the pipeline and increases its hydraulic resistance. This in turn leads to a decrease in the capacity of the pipeline and increase the energy consumption of oil transportation [1-5].

To maintain the indicators of transport capacity and energy efficiency of the pipeline operation at the required level, its inner surface is periodically cleaned of paraffin deposition [6,7]. Various devices are used to clean oil pipelines. The greatest efficiency is provided by scrapers with different design and technical characteristics [1,2].

It is customary to calculate the dynamics of the purification device in the pipeline approximately according to the parameters of the design or actual regular modes of oil pumping. The operating flow of oil in the pipeline during the process of purification from paraffin deposition is considered a constant value [1,2].

This does not allow to determine the speed of the cleaning device in the pipeline, the time of its approach to the end of the pipeline with the required accuracy, which complicates the implementation of the technological process. The results of studies of the gas-dynamic processes regularity during motion of the current devices in gas pipelines are given in [8-11]. Regarding the movement of cleaning devices in oil pipe.

It is necessary to be able to reliably predict the location of the cleaning device on the route at any time, as well as the time of its approach to the alarms and reception chambers on the oil pumping station (OPS) for operational control of the pipeline cleaning process from paraffin deposition. This work is devoted to solving this problem.

The purpose of such research is to improve the technology of purification of the pipeline from paraffin deposition by taking into account changes in the inner diameter and additional hydraulic resistance of the plug from the mixture of oil and purification products to the capacity of the pipeline, energy efficiency of oil transportation and pipeline speed. During the movement of the purification device through the pipeline cavity at each time the hydraulic resistance of the linear part decreases due to the restoration of the live cross section of the clean pipe, which causes a change in the mode of centrifugal pumps of pumping stations. In addition, as practical experience shows, before the purification device, a plug of a mixture of oil and purification products, mainly paraffin, is formed.

This plug causes additional hydraulic resistance, which affects the capacity of the pipeline and energy costs for oil transportation as well.

Thus, a certain value of the capacity and energy efficiency of the main oil pipeline corresponds to each position of the treatment device in the cavity of the pipeline.

The hydrodynamic process of moving the cleaning device in the cavity of the pipeline is unstable [10]. Given the low speed of the cleaning device (1-2) m/s, this process can be considered with sufficient accuracy for engineering calculations as a sequence of quasi-steady states, each of which corresponds to a certain position of the cleaning device in the pipeline cavity [12-15].

It is assumed that due to the perfect design of the cleaning device and the effective technology of the treatment process, the movement of the cleaning device through the pipeline leads to the restoration of the inner diameter of the pipe, which corresponded to the condition of the clean pipe. In addition, in contrast to the calculation methods available [1,2], it is taken into account the fact that before the purification device the plug, which is filled with a mixture of transported oil and purification products, in the purification process is formed.

2. The method of calculating the parameters of the cleaning device of the pipeline

In the steady-state mode of pumping oil through an oil pipeline equipped with one OPC, the energy balance equation for each point in time could be written as follows:

$$P_{ps} = P_{ac} + P_{pl} + P_{bc} + \Delta P_{td} + P_{end}, \tag{1}$$

where P_{ac} – pressure losses in the section of the pipeline cleaned of paraffin deposition; P_{pl} – pressure losses in the section of the pipeline formed by a mixture of oil and purification products; P_{bc} – pressure losses in the section of the pipeline, which has not yet reached, so it is not cleaned of paraffin deposition; ΔP_{td} – pressure losses on the treatment device; P_{end} – technologically necessary oil pressure at the end of the pipeline.

The proposed method of hydrodynamic calculations can be used when using different design cleaning devices, while in formula (1) should be substituted the appropriate amount of pressure loss ΔP_{td}.

The oil pressure at the end of the section of the pipeline to be cleaned P_{end}, is necessary for the implementation of technological procedures for receiving the cleaning device at the pumping station.

It is assumed that in the cleaned and untreated sections of the pipeline rheological properties of the transported oil correspond to the properties of the Newtonian fluid. if the Newtonian fluid is transported, the method of hydraulic calculation of the pipeline does not require additional research.

It is believed that the rheological characteristics of the liquid plug formed from the cleaning products before the cleaning piston correspond to the characteristics of the viscoplastic fluid [6,7,16], the features of hydraulic calculation of the oil pipeline during transportation of viscoplastic liquid are considered below.

The length of the liquid plug l_{pl}, formed by the purification products, is expressed as a function of the linear coordinates of the purification device location in the pipeline

$$l_{pl}=\left[\left(\frac{D_{ac}}{D_{bc}}\right)^2-1\right]\cdot x\,, \tag{2}$$

where D_{ac} – the inner diameter of the cleaned section of the pipeline; D_{bc} – the inner diameter of the untreated section of the pipeline.

In the case of pumping viscoplastic fluid, the method of hydraulic calculation of the pipeline depends on the mode of its movement. First of all, it is necessary to determine the mode of movement of the viscoplastic fluid. it is necessary to predefine the Headstream parameter for this

$$He=\frac{\tau_o D_{bc}^2\rho_{pl}}{\eta_p^2}\,, \tag{3}$$

where τ_o – the maximum dynamic shear stress of the viscous plastic fluid at the pumping temperature; ρ_{pl} – the density of the liquid plug at the pumping temperature; η_p – plastic viscosity of the liquid plug at the pumping temperature.

For the critical Reynolds number, which separates the laminar and turbulent modes of motion of a viscoplastic fluid in a pipeline, proposed by us formulas obtained by processing experimental data are used [16]:

- for the Headstrom numbers' range from 10^3 to 10^5

$$Re_{cr}^*=1000+173{,}72\cdot \ln He\,; \tag{4}$$

- for the Headstrom numbers' range from 10^5 to 10^8

$$Re_{cr}^*=1450+141{,}15\cdot \ln He\,. \tag{5}$$

It was found criteria that characterize the movement of viscoplastic fluid. Bingham Reynolds number

$$Re_{pl}=\frac{4Q\rho_{pl}}{\pi D_{bc}\eta_p}\,, \tag{6}$$

where Q – volumetric flow rate of liquid in the pipeline.

Ilyushin's criterion and the generalized Reynolds number for a liquid plug

$$I=\frac{\pi D_{bc}^3\tau_o}{4Q\eta_p}\,, \tag{7}$$

$$Re^*=\frac{8\,Re_{pl}}{I+2\left(1+\sqrt{9+I}\right)}\,. \tag{8}$$

If the condition is met

$$Re^*<Re_{cr}^*\,, \tag{9}$$

the mode of movement of the liquid plug is laminar, otherwise the mode of movement of the viscoplastic liquid in the plug in front of the cleaning device is turbulent.

A generalized Leibenzon model was used to calculate the coefficient of hydraulic resistance during the movement of a viscoplastic fluid in an oil pipeline [16]

$$\lambda_{pl}=\frac{A}{Re^{*m}}\,, \tag{10}$$

where A,m – coefficients that depend on the mode of movement of the viscoplastic fluid in the pipeline.

For laminar mode

$$A=64\,;\qquad m=1\,; \tag{11}$$

for laminar mode

$$A=3{,}13\,He^{-0{,}34}\;;\quad m=1{,}12\,He^{-0{,}2}\,. \tag{12}$$

The energy balance equation (1) taking into account formulas (2)-(12) for an arbitrary position of the purification device in the pipeline takes the form

$$P_{ps}=\frac{8}{\pi^2}Q_x^2\left[\frac{\lambda_{ac_x}\rho}{D_{ac}^5}x+\frac{\lambda_{pl_x}\rho_{pl}}{D_{bc}^5}l_{pl}+\frac{\lambda_{bc_x}\rho}{D_{bc}^5}\left(L-x-l_{pl}\right)\right]+$$

$$+\Delta P_{td}+P_{end}\,, \tag{13}$$

where P_{ps} – oil pressure at the outlet of the OPS with taking into account technological limitations; ρ – density of oil transported by the pumping conditions; Q_x – operating flow of oil in the pipeline, the function of the linear coordinates of the cleaning piston's position in the pipeline; λ_{ac_x} – coefficient of hydraulic resistance for the cleaned section of the pipeline; λ_{bc_x} – coefficient of hydraulic resistance for the untreated section of the pipeline; L – the length of the pipeline.

As evidenced by the practice of operation of pipelines, paraffin deposition are placed unevenly along the length and perimeter of the pipe. Therefore, the concept of equivalent, constant in length inner diameter of the untreated section of the pipeline, is widely used for analytical research [1,2,17,18].

The pressure created by OPS pumps according to the sequential scheme of their work is found by the formula

$$P_{ps} = P_{sup} + \sum_{i=1}^{n} P_i \,, \tag{14}$$

where P_{sup} – the pressure of the support pump for oil supply Q_x; P_i – pressure of the i-th main pump for oil supply Q_x; n – the number of main pumps running on the OPS in series.

Polynomial dependences are used to describe the characteristics of the pressure characteristics of pumps

$$P_{sup} = \left(a_{sup}^{н} Q_x^3 + b_{sup}^{н} Q_x^2 + c_{sup}^{н} Q_x + d_{sup}^{н}\right)\rho g \,, \tag{15}$$

$$P_i = \left(a_i^{н} Q_x^3 + b_i^{н} Q_x^2 + c_i^{н} Q_x + d_i^{н}\right)\rho g \,, \tag{16}$$

where $a_{sup}^{н}, b_{sup}^{н}, c_{sup}^{н}, d_{sup}^{н}$ – coefficients of the mathematical model of the pressure characteristic of the support pump, found by the method of least squares by its graphical characteristic; $a_i^{н}, b_i^{н}, c_i^{н}, d_i^{н}$ – coefficients of the mathematical model of the pressure characteristic of the i-th main pump, found by the method of least squares by its graphical characteristic.

The efficiency characteristics of the pumps are also described by polynomial dependences

$$\eta_{sup} = a_{sup}^{\eta} Q_x^3 + b_{sup}^{\eta} Q_x^2 + c_{sup}^{\eta} Q_x \,, \tag{17}$$

$$\eta_i = a_i^{\eta} Q_x^3 + b_i^{\eta} Q_x^2 + c_i^{\eta} Q_x \,, \tag{18}$$

where $a_{sup}^{\eta}, b_{sup}^{\eta}, c_{sup}^{\eta}$ – coefficients of the mathematical model of the support pump efficiency, found by the method of least squares by its graphical characteristic; $a_i^{\eta}, b_i^{\eta}, c_i^{\eta}$ – coefficients of the mathematical model of the efficiency characteristic of the i-th main pump, found by the method of least squares by its graphical characteristic.

Based on our previous developments [16,19], a computational algorithm and a computer program have been created, which allow to determine the operating oil consumption and energy efficiency of the main oil pipeline operation during the movement of the treatment device through the pipeline cavity. The method includes the following elements:

- block of mathematical modelling of physical properties and characteristics of pump units according to formulas (14)-(18);
- block for calculating the parameters of the OPS, taking into account the technological limitations of pressure and oil consumption;
- block of hydraulic calculation of the pipeline's linear part taking into account the above formulas (2)-(13);
- unit for determining the energy efficiency of the pipeline, which provides for the calculation of specific costs of electricity for pumping oil during the process of cleaning the pipeline from paraffin deposition.

The block of hydraulic calculation of the pipeline's linear part during the movement of oil, characterized by Newtonian properties, is based on the use of a modified Colbrook formula to calculate the coefficient of hydraulic resistance [16,19].

All other blocks of the computational algorithm and computer program are described in detail in the works [1,16,19].

This method of calculating the mode of operation of the pipeline in the process of its purification from paraffin deposits has no restrictions on the viscosity of oil, provided that it is characterized by the properties of Newtonian fluid.

The method of determining the capacity and energy efficiency of the pipeline in the period of cleaning from paraffin deposition involves taking into account the technological limitations of pressure and oil flow, which ensure the strength of the pipeline and the operation of pumping units without cavitation.

3. The mode of operation of the pipeline during cleaning of paraffin deposition

Approbation of the technique was performed for the section of the main oil pipeline with a length of 100 km with an internal diameter of 0.702 m, the difference of geodetic marks of the oil pipeline's end and beginning is 50 m. The initial data are close to the characteristics and modes of oil pipelines operation in Ukraine.

Mathematical models of the main pump's characteristics are as follows:

- for pressure (m) from giving (m^3/h)

$$H = -1{,}513 \cdot 10^{-9} Q_h^3 + 4{,}057 \cdot 10^{-6} Q_h^2 - 1{,}973 \cdot 10^{-2} Q_h + 320;$$

- for efficiency (%) of the feed (m^3/h)

$$\eta = 1{,}598 \cdot 10^{-9} Q_h^3 - 1{,}882 \cdot 10^{-5} Q_h^2 + 7{,}077 \cdot 10^{-2} Q_h \,.$$

Mathematical models of the support pump's characteristics are as follows:

- for pressure (m) from giving (m³/h)

$$H_{sup} = -6{,}134 \cdot 10^{-10} Q_h^3 + 5{,}195 \cdot 10^{-7} Q_h^2 - 2{,}848 \cdot 10^{-3} Q_h + 122,$$

- for efficiency (%) of supply (m³/h)

$$\eta_{sup} = 5{,}465 \cdot 10^{-10} Q_h^3 - 1{,}078 \cdot 10^{-5} Q_h^2 + 5{,}446 \cdot 10^{-2} Q_h .$$

The physical properties of oil under pumping conditions are as follows: density $\rho = 877$ kg/m³, kinematic viscosity 39·10⁻⁶ m²/s. The properties of the liquid plug in front of the cleaning device, which is characterized by the rheological characteristics of the viscoplastic fluid, are as follows: the maximum dynamic shear stress $\tau_o = 5$ Pa, plastic viscosity η_p = 0.1 Pa·s, density ρ_{pl} = 880 kg/m³.

We assume that the inner equivalent diameter of the pipeline, taking into account the deposition of paraffin, was amounted $D_{ho} = 0{,}680$ m, the inner diameter r of the cleaned pipe $D_o = 0{,}702$ m. In the process of cleaning the cavity of the pipeline support pump and two main pumps worked in series.

Calculations of the pipeline's capacity during the passage of the cleaning device through the pipeline are carried out by two methods: without taking into account and taking into account the additional hydraulic resistance of the liquid plug formed by oil and purification products – mostly paraffin.

It is constructed by the computer program graphical dependences of capacity and specific expenses of the electric power as function of a linear coordinate of an arrangement of the clearing device on the route of the oil pipeline based of multivariate calculations results (Fig. 1 and 2).

Figure 1 shows that if the variable hydraulic resistance of the liquid plug is not taken into account, then the movement of the treatment device through the cavity of the pipeline and cleaning the pipeline causes a significant increase in capacity from 1668 m³/h to 1807 m³/h.

If the effect of the hydraulic resistance of the viscoplastic fluid plug is taken into account, the movement of the cleaning piston by the oil pipeline reduces the capacity from 1668 m³/h to 1614 m³/h.

As Figure 1 shows, for this case, the relationship between oil consumption (m³/h) and the coordinate of the cleaning device (km) is adequately described by the following mathematical model:

$$Q_{h_x} = 1668 + 1{,}220x + 0{,}0017x^2 ,$$

taking into account the hydraulic resistance of the liquid plug:

$$Q_{h_x} = 1668 - 0{,}436x + 0{,}0011x^2 .$$

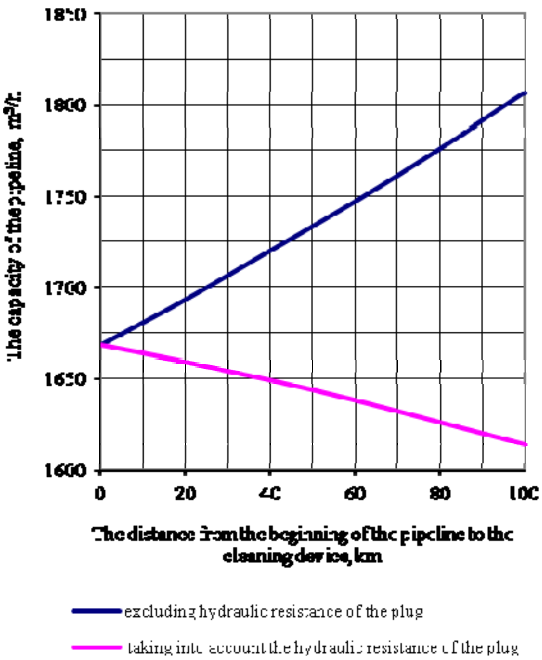

Fig. 1. Dependence of the pipeline's capacity on the site the location of the cleaning device in the cavity of the pipe

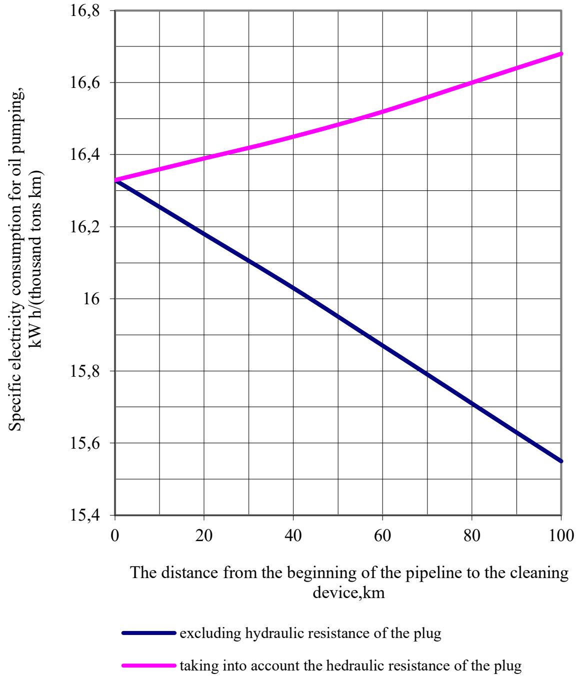

Fig. 2. Dependence of specific costs of electricity for transportation oil pipeline from the location of the treatment plant in the cavity of the pipe

Figure 2 shows that if the variable hydraulic resistance of the liquid plug is not taken into account, the movement of the treatment device through the cavity of the pipeline and cleaning the pipeline causes a significant reduction in specific electricity consumption for oil transportation from 16.33 kW·h/(thousand tons · km) to 15.55 kW·h/(thousand tons · km). If the influence of the hydraulic resistance of the plug from the viscoplastic fluid is taken into account, the movement of the cleaning piston through the pipeline causes an increase in specific electricity consumption for oil transportation from 16.33 kW·h/(thousand tons · km) to 16.68 kW·h /(thousand tons · km).

For the case under consideration, the relationship between the specific electricity consumption (kW·h)/(thousand tons · km) and the linear coordinate of the location of the cleaning piston (km) is adequately described by such mathematical models:

- without taking into account the hydraulic resistance of the liquid plug

$$W_e = 16{,}33 - 7{,}400 \cdot 10^{-3} x - 4{,}115 \cdot 10^{-6} x^2 ,$$

- taking into account the hydraulic resistance of the liquid plug

$$W_e = 16{,}33 + 2{,}722 \cdot 10^{-3} x + 7{,}842 \cdot 10^{-6} x^2 .$$

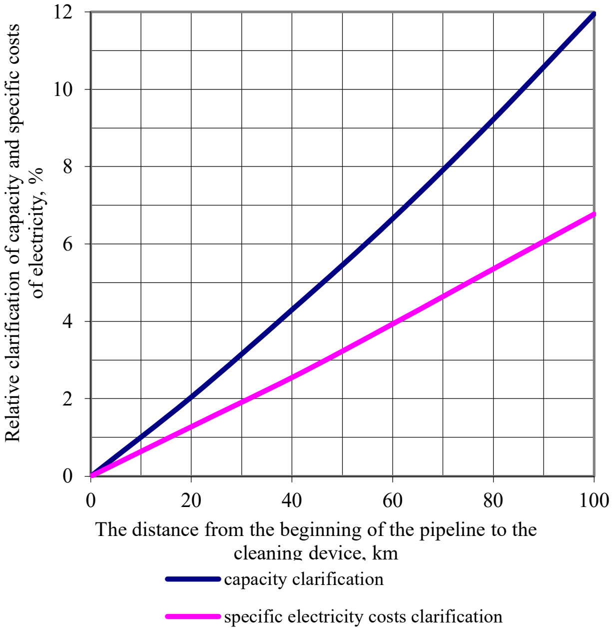

Fig. 3. Relative clarification of the capacity of the pipeline and specific electricity consumption if the hydraulic resistance of the plug is taken into account

Figure 3 illustrates the relative refinement of the capacity of the pipeline and the specific cost of electricity for the cleaning process in the case if the hydraulic resistance of the plug formed in front of the treatment device.

Having the regularity of the change in oil flow from the position of the purification device in the cavity of the pipeline, the equation is obtained, which characterizes the change in the speed of the purification device v (m/s) with changes in the linear coordinate (km).

For the case under consideration, the following expressions are obtained:

- without taking into account the hydraulic resistance of the liquid paraffin plug

  $v = 1{,}276 + 9{,}331 \cdot 10^{-4} x + 1{,}300 \cdot 10^{-6} x^2$;

- taking into account the hydraulic resistance of the liquid paraffin plug

  $v = 1{,}276 - 3{,}337 \cdot 10^{-4} x - 8{,}410 \cdot 10^{-7} x^2$.

The probability of approximation of all proposed mathematical models exceeds 99%.

It is necessary to predict the location of the cleaning device at each point in the process during the implementation of the pipeline cleaning.

The initial equation for solving this problem is the obtained pattern of changes in the speed of the treatment device from the linear coordinate, which in the general case could be represented as:

$$v = Ax^2 + Bx + C . \tag{19}$$

An expression is written that relates the elementary change in the travel time of the cleaning piston $d\tau$ and an elementary change in its position in the pipeline

$$d\tau = \frac{dx}{Ax^2 + Bx + C} . \tag{20}$$

The time of the treatment device movement for its arbitrary position in the cavity of the pipeline

$$T_x = \int_0^x \frac{dx}{Ax^2 + Bx + C} . \tag{21}$$

As a result of integrating the right-hand side of equation (21), it is obtain:

if $\Psi = 4AC - B^2 < 0$

$$T_x = \frac{1}{\sqrt{-\Psi}} ln\left[\frac{\left(2Ax + B - \sqrt{-\Psi}\right)}{\left(2Ax + B + \sqrt{\Psi}\right)} \cdot \frac{\left(B + \sqrt{\Psi}\right)}{\left(B - \sqrt{\Psi}\right)}\right] , \tag{22}$$

if $\Psi > 0$

$$T_x = \frac{2}{\sqrt{\Psi}}\left[arctg\,\frac{2Ax + B}{\sqrt{\Psi}} - arctg\,\frac{B}{\sqrt{\Psi}}\right] . \tag{23}$$

Figure 4 illustrates the relationship between the duration of the treatment process and the linear coordinate of the location of the cleaning device in the pipeline for the above conditions. The dependence of the pipeline's capacity on the duration of the process of its purification is shown in Figure 5.

Figure 6 illustrates the obtained dependence of the speed of the cleaning piston on the time of its movement in the pipeline.

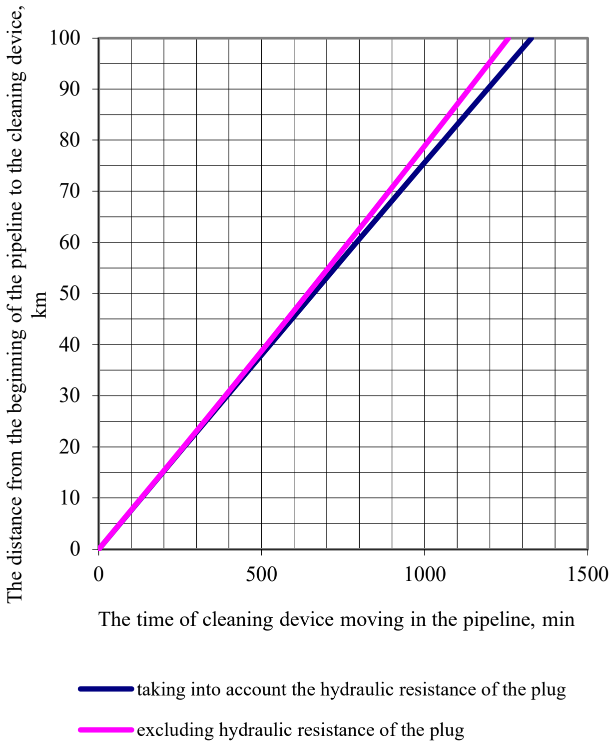

Fig. 4. The relationship between the duration of the cleaning process and linear the coordinate of the location of the cleaning device in the pipeline

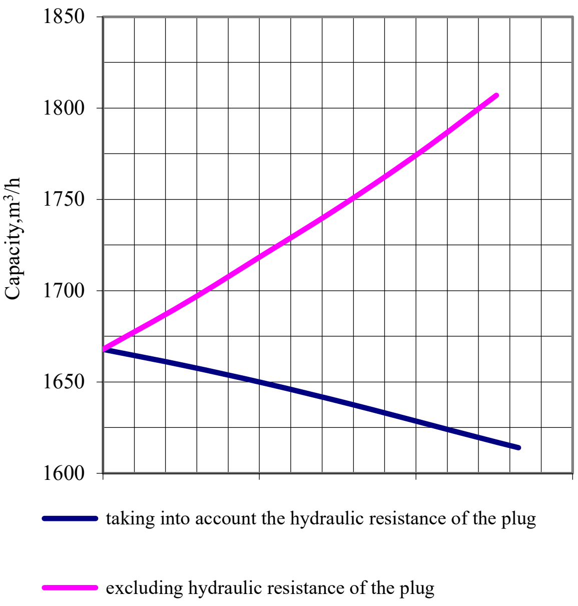

Fig. 5. Dependence of the pipeline's capacity on the duration of the cleaning process

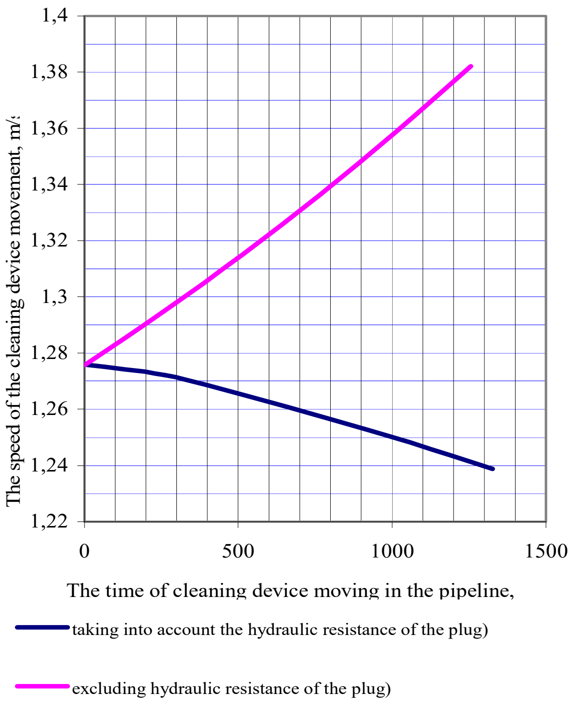

Fig. 6. The relationship between the duration of the cleaning process and speed movement of the cleaning device in the pipeline

4. Conclusions

The movement of the cleaning piston and the cleaning of the inner cavity of the pipeline by its causes a change in operating costs and specific costs of electricity for pumping oil. In the cleaning process, the hydraulic resistance of the linear part of the pipeline significantly depends on the additional hydraulic resistance of the plug, which is formed in front of the purification device and contains a mixture of oil and paraffin. This plug is characterized by the properties of the viscoplastic fluid described by the rheological model of Shvedov-Bingham.

It was developed the method that allows predicting the capacity and energy efficiency of the pipeline operation for each position of the cleaning device in the pipeline and each time of the treatment process.

The proposed method allows to specify the duration of the process of cleaning the pipeline and the time of arrival of the treatment device at the end of the pipeline, which increases the efficiency of this process.

It was proved that the dependence of capacity, energy efficiency and cleaning speed both on the location of the treatment device in the pipeline cavity and on the duration of the cleaning process describes polynomial functions of another degree reliably.

It was specified by (5-12)% the capacity of the pipeline, the specific consumption of electricity for oil transportation, the dynamics of the purification device and the time of its arrival at the end of the pipeline by taking into account the additional resistance of the paraffin plug for cleaning the model pipeline.

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