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Simulation of oil pipeline shutdown and restart modes

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ABSTRACT
The paper is devoted to the simulating of non-stationary processes of shutdown and restart on the example of a section of the Zhetybai-Uzen "hot" oil pipeline. A mathematical model of thermal-hydraulic calculation is given taking into account the rheological properties of the pumping oil. The special module of the SmartTran software developed by the work's authors carried out the calculations. In the calculations, the decrease in time of oil temperature in the pipeline during cooling and the increase in oil pressure, temperature, velocity after the restart are determined. In addition, the calculations determine the power of pumping units, heating furnaces and the power consumption, which are necessary for restart of the pipeline after the shutdown. Simulation the processes of the pipeline cooling and restart after a shutdown makes it possible choosing the optimum parameters of pumping units at pumping stations and the time of safe shutdown of the oil pipeline.

Keywords: simulation, oil pipeline, transportation, shutdown, restart, software module.

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Introduction

Simulation of the shutdown, cooling and restart of the pipeline is very important for constructing a process flow diagram of the pipeline operation acceptable modes. The start of the non-isothermal oil pipeline section after the shutdown is one of the most complex technological process governing the entire pipeline operation. Short-term shutdown of the main pipeline section and its restart requires extreme care due to emergency risk. This is because the oil cools down and the oil viscosity increases sharply due to the temperature decrease during the short-term shutdown of the section. Pressure losses in the pipeline increase significantly and for the restart of section greater pressures of pumping units are required, which, in turn, create the emergency risk.

Simulation of the pipeline cooling and restart after a shutdown makes it possible to analyze various cases to determine the safe mode of the pipeline launching. Calculations of the shutdown and restart of the pipeline allow choosing the optimum parameters of pumping units and the safe shutdown time.

Mathematical setting of the problem

The oil pipeline shutdown and restart process is a non-stationary pumping mode, because of the oil pressure, temperature and flow rate are varying with time. The calculation of the non-stationary process requires consideration of the differential equations of motion and energy.

In view of the fact that the length L of the oil pipeline section is much greater than its internal diameter D_1 (L>>D_1), the problem is considered in a one-dimensional settlement.

The energy equation determines the temperature along the pipeline, depending on the velocity, in view of the prevailing effect of convection heat transfer compared to conduction for oil pumping. Therefore, the conduction heat transfer can be neglected in the energy equation.

In that case, the energy equation for the main oil pipeline section, taking into account the heat of friction and oil heating at the stations, is written as [1, 2, 3]:

$$\frac{\partial T}{\partial t} = -u(T)\frac{\partial T}{\partial x} - \frac{4k}{\rho D_1 c_p}(T - T_w(x,t)) + \frac{\zeta u^3}{2c_p D_1} + \frac{\sum_{i=1}^{n} R_i(x)\Delta T_i^{pd}}{\Delta t} \quad (1)$$

where T, T_w are the temperatures of oil and ground, respectively; ρ, c_p, u are the density, the heat capacity, and the velocity of oil, respectively; k is the heat transfer coefficient, ζ is the hydraulic resistance coefficient, n is the number of midpoint oil heating stations, $R_i(x)$ is the existence function of the heating station, equal to 1, if the station is at a point x, and 0 otherwise, ΔT_i^{pd} is the value of oil heating at the i-th station.

The values of (x), $T_w(x)$, $k(x)$, $\zeta(x)$ are the functions of x, i.e. they possess different values along the pipeline. The term $\zeta u^3/2c_pD_1$ expresses the kinetic energy dissipation of the oil flow.

The outlet temperature of the initial station is set as the boundary condition for the equation (1). The temperature at the inlet of end station can be uniquely calculated by solving the equation (1).

The heat transfer coefficient k through the wall of pipeline is determined by the formula [4, 5]:

$$\frac{1}{kD_1} = \frac{1}{D_1\alpha_1} + \frac{1}{D_{out}\alpha_2} + \sum_{i=1}^{n}\frac{1}{2\lambda_i} ln\left(\frac{D_{i+1}}{D_i}\right) \quad (2)$$

where α_1 is the internal heat transfer coefficient, α_2 is the external heat transfer coefficient, λ_i is the thermal conductivity coefficient, D_i, D_{i+1} are the inner and outer diameters of the i-th layer (pipe wall, insulation), respectively, D_1, D_{out} are the inner and outer diameters of the pipeline, respectively.

The Forchheimer formula [4] is used to calculate the external heat transfer coefficient α_2:

$$\alpha_2 = \frac{2\lambda_{gr}}{D_{out} ln\left[\frac{2H}{D_{out}} + \sqrt{\left(\frac{2H}{D_{out}}\right)^2 - 1}\right]}$$

where λ_{gr} is the thermal conductivity coefficient of the ground, H is the pipeline depth to its axis.

The internal heat transfer from oil to the wall of pipeline α_1 is defined as [6]:

$$\alpha_1 = \frac{\lambda_{\text{oil}}}{D_1} \cdot Nu$$

where λ_{oil} is the oil thermal conductivity coefficient, Nu is the Nusselt's number of oil-to-pipe wall heat transfer during forced convection in an enclosed volume.

In case the pipeline is stopped, so $u=0$, then the thermal energy equation (1) takes the simpler form:

$$\frac{\partial T}{\partial t} + \frac{4k_1}{\rho c_p D_1}(T - T_w) = 0 \quad (3)$$

The equation (3) is used to calculate the oil cooling temperature in a stopped pipeline; the heat transfer coefficient k1 can be easily obtained by the formula (2).

The energy equation (1) is solved simultaneously with the motion equation, which determines the correlation between oil pressure and flow rate [4]:

$$\rho\frac{\partial u}{\partial t} + \frac{\partial p}{\partial x} = -\zeta(Re,\varepsilon)\frac{\rho u|\vec{u}|}{2D_1} - \rho g sin\beta(x) \quad (4)$$

where p is the oil pressure in the pipe, Re is the Reynolds number, ε is the pipe relative roughness, $\zeta(Re,\varepsilon)\frac{\rho u|\vec{u}|}{2D_1}$ determines the pressure drop,

$\rho g \frac{dz}{dx} sin\beta(x)$ is the static pressure change due to the profile of pipeline.

The temperature-viscosity and temperature-heat capacity relationships are determined by the standard formulas [2] - [4]:

$$\rho(T) = \rho_{20}[1 + \xi(20 - T)],$$
$$\mu(T) = a \cdot e^{-bT}, \quad (5)$$
$$c_p(T) = \frac{1}{\sqrt{\rho_{20}}}(53357 + 107.2 \cdot T)$$

where ρ_{20} is the oil density at 20°C; ξ is the volumetric expansion coefficient of the oil mixture (ξ = 0.000738 1/°C); a,b are empirical constants.

The oil inlet pressure at the end station is set as the boundary condition of the equation (4). The outlet pressure at the initial station is created by the operation of pumping units for transportation of the required oil volume along the length of the pipeline.

The hydraulic resistance coefficient is calculated depending on the oil flowing regime in the pipe [7]-[9] (Table 1).

The Reynolds number Re includes the oil viscosity coefficient $\mu(T)$, which can be found from the equation (1) if we know the oil temperature.

The system of equations (1)-(5) is solved together for each time step by the numerical method [10]-[13]. The computational domain of the equations coincides with the pipeline length, and is divided into the computational nodes with 1 m distance.

An explicit scheme is used for discretization of the equations (1), (3). The time step for stability of the explicit difference scheme for (1), (3) is chosen from the Courant condition [10], [11]. The difference scheme of the equation (4) was obtained by an implicit scheme, which, as it is known, is stable [9], [10].

The difference equations are reduced to a system of linear algebraic equations, and are solved by the iterative methods [10]-[14].

The special library was developed to speed up the calculation. The calculations of oil pressure and temperature were carried out by the software developed in C#. The interface window of the software is presented in Fig. 1.

Table 1 – Determination of the hydraulic resistance coefficient

Flow regime	Condition	Determination of ζ
Laminar flow regime	$Re \le 2040$	$64/Re$
Transition regime	$2040 < Re \le 2800$	$1.176 * 10^{-5} * Re^{1.035}$
Turbulent flow regime (skin friction zone)	$2800 < Re \le 17.5/\varepsilon$	$0.3164/Re^{0.25}$
Turbulent flow regime (mixed friction zone)	$17.5/\varepsilon < Re \le 531/\varepsilon$	$\frac{0.206\varepsilon^{0.15}}{Re^{0.1}}$
Turbulent flow regime (quadratic friction zone)	$531/\varepsilon < Re$	$0.11\varepsilon^{0.25}$

Discussion of the calculated data of shutdown and restart of the pipeline

To simulate the shutdown and restart process of a given section of the main oil pipeline, it is necessary to select the calculation type “shutdown and restart mode” on the tool bar of the main window (see Fig. 1) and then indicate the stop time in hours.

Next the following calculation parameters are entered:

- the type of pumped oil;
- the list of operating pumps before shutdown and after restart;
- the list of operating preheaters before shutdown and after restart;
- the oil preheat temperature at the initial station.

Note that it doesn’t take to set the pipeline section’s flow rate, because the oil flow rate before the shutdown and after the restart will be calculated by the software module according to the parameters of the operating pumps and preheaters.

Fig. 1 shows the main window domains for entering the initial parameters and running the calculation: the domain №1 for selection and starting the mode, the domain №2 for entering the operational parameters for each pipeline station.

After entering all parameters, the calculation mode of the shutdown and restart of the pipeline is started.

The simulation results of the shutdown and restart of pipeline are presented in Fig. 2-6. Fig. 2 shows the calculated data of the hydraulic slope (top plot), the pressure (middle plot), oil and ground temperatures (bottom plot) before the shutdown of the "Zhetybai – Uzen" pipeline section. The calculation results are presented in the forms of plot and table in a separate window: oil flow rate, distributions of oil temperature, pressure in the pipe, hydraulic slope along the pipeline, as well as a list of operating pumps and preheaters at the stations, the amount of consumed electricity and fuel (Fig. 2).

Fig. 3 presents the calculation results of the oil cooling process within 6 hours of shutdown and at the time of restart of the "Zhetybai – Uzen" pipeline. The oil temperature decreased as a result of cooling during the shutdown (see Fig. 3) compared with the oil temperature distribution before the shutdown of pipeline (see Fig. 2).

Figure 1 – The window for entering the initial parameters, and the calculation of the pipeline shutdown and restart

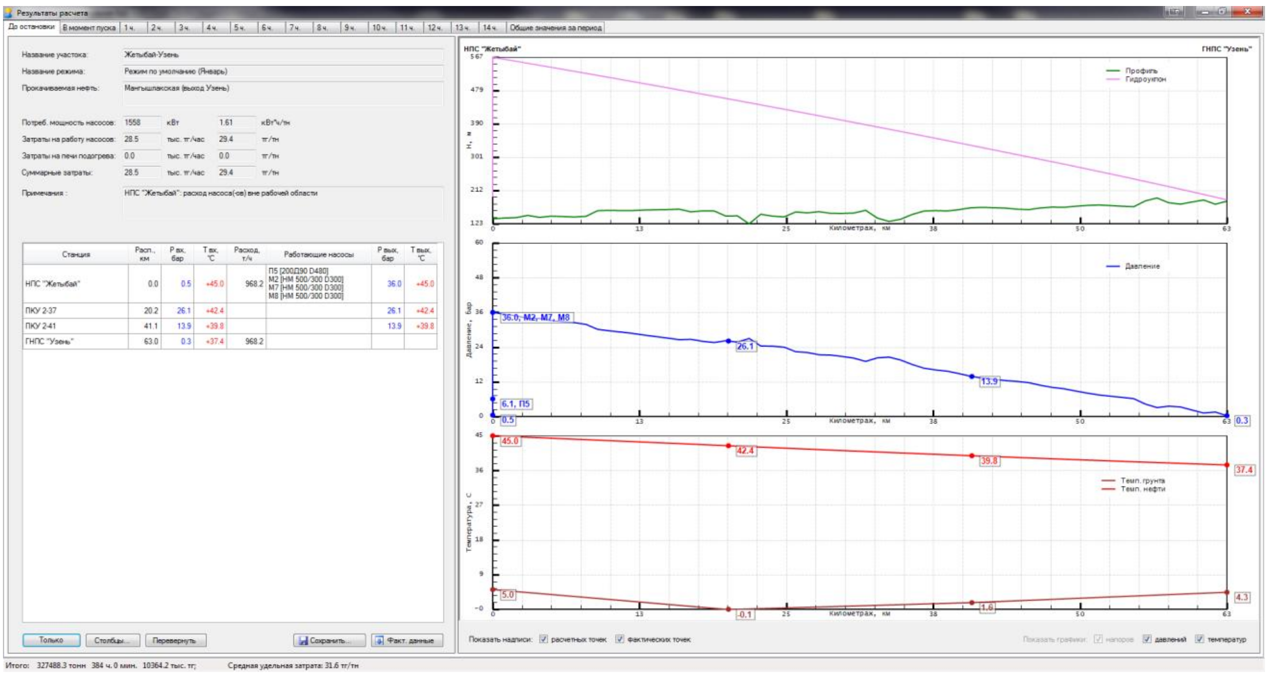

Figure 2 – Computed data before shutdown of the "Zhetybai-Uzen" pipeline

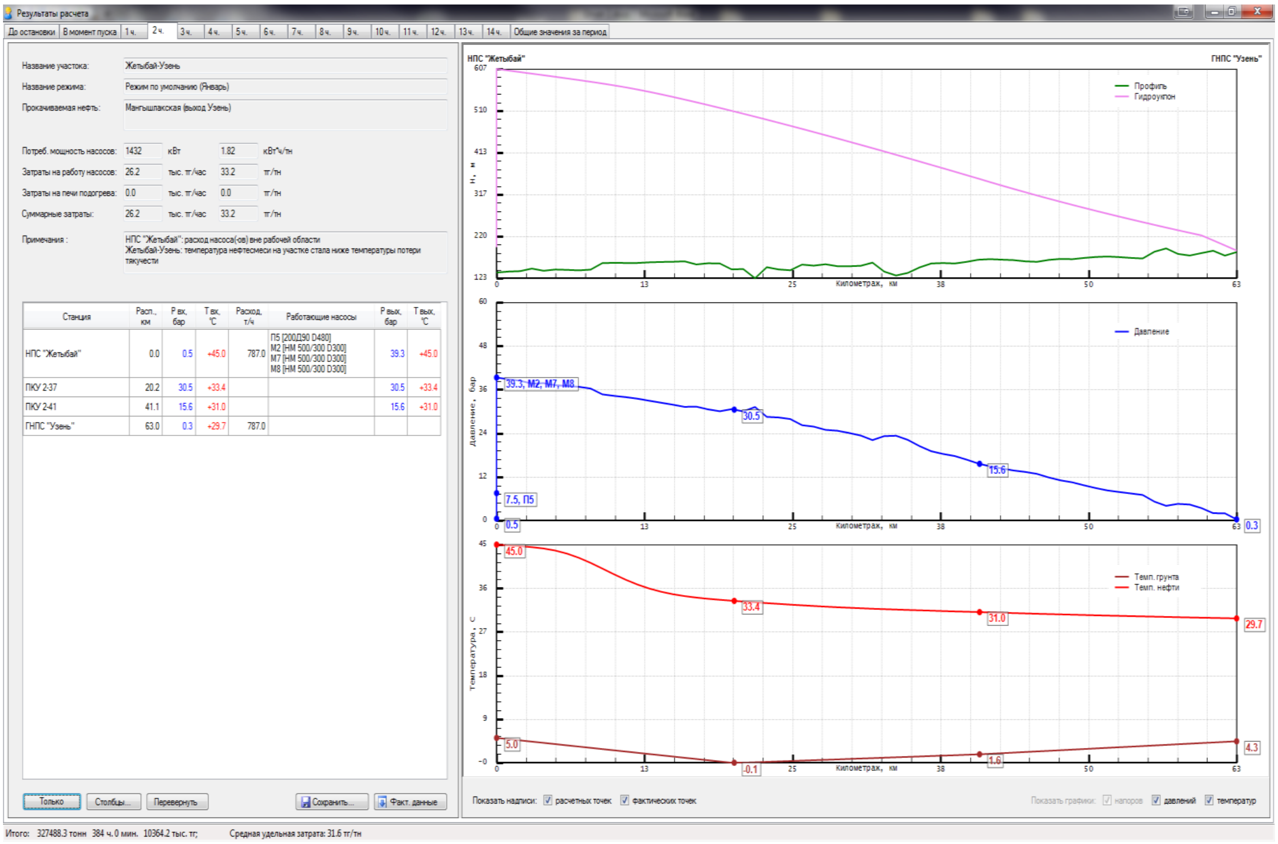

Figure 4 - Computed data 2 hours after the restart of the "Zhetybai – Uzen" pipeline

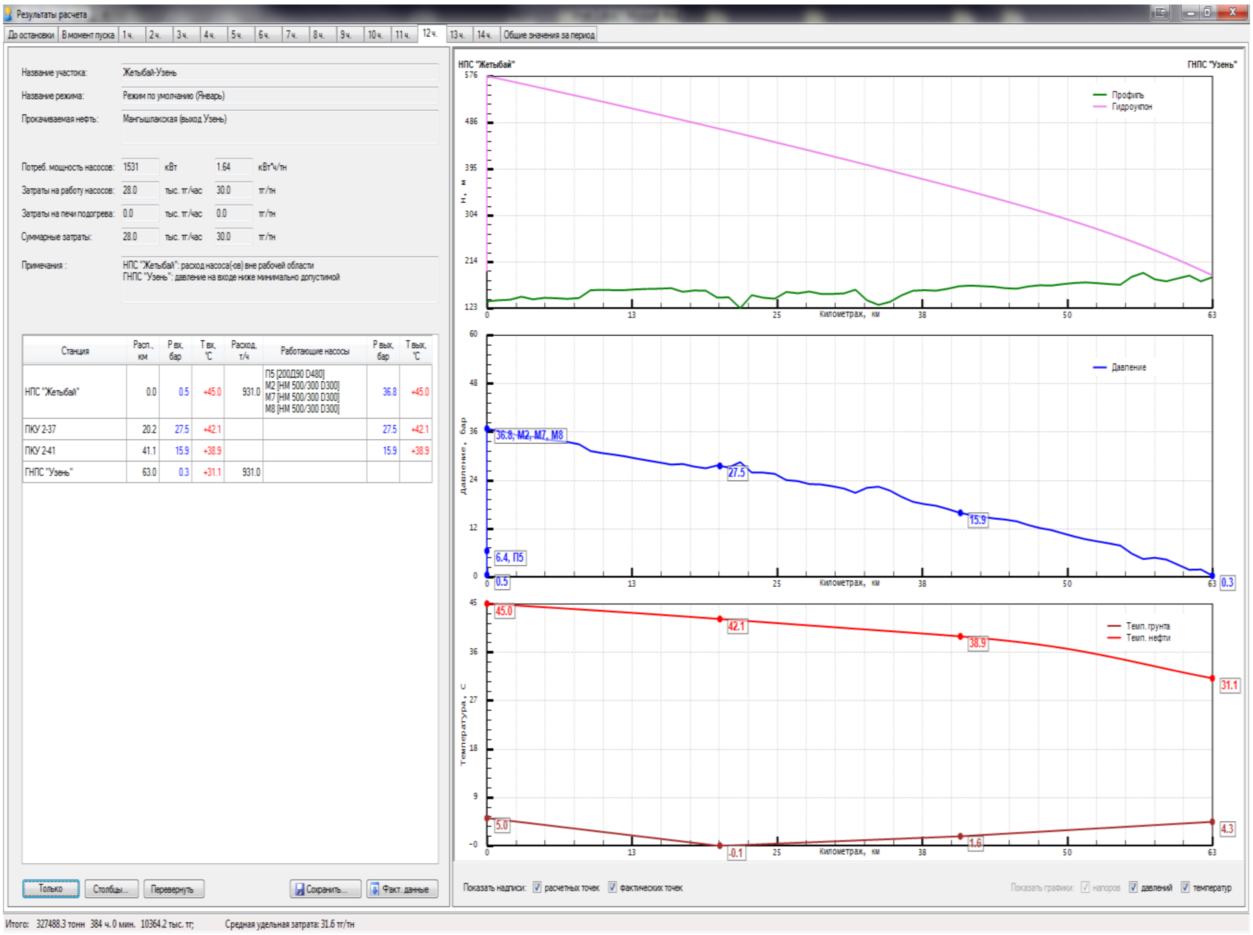

Figure 5 - Computed data 12 hours after the restart of the "Zhetybai – Uzen" pipeline

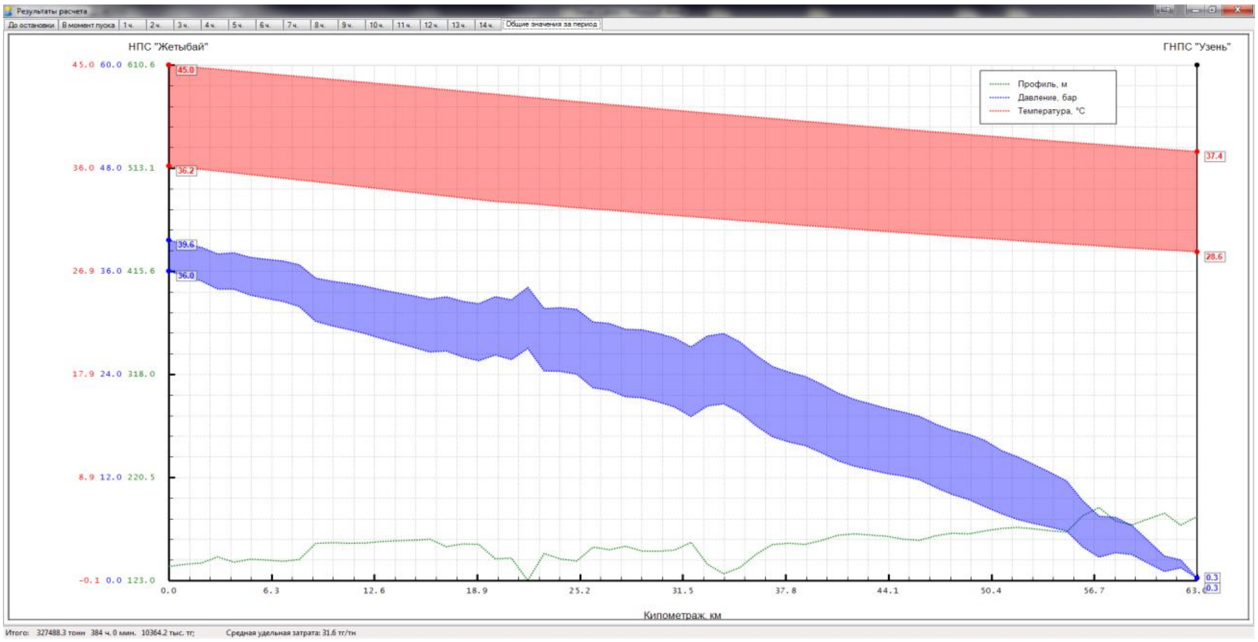

Figure 6 - Total change in the oil pressure and temperature over the entire period after the restart of the Zhetybai-Uzen pipeline

Fig. 4, 5 show the dynamics of the oil parameters in time after the restart of pipeline: hydro-slope, pressure, temperature, and flow rate.

The state of oil flow 2 hours after restarting (see Fig. 4) is characterized by the values of the oil flow rate, pressure and temperature; those make 737 t/h, 39.3 bar and 45°C, respectively. These data indicate that the oil temperature rises to 45 °C in the heating furnaces. However, according to the calculation data, the flow rate value is less than before the shutdown, and the pressure value, on the contrary, is greater. This is explained by the fact that an increase in oil viscosity in the pipeline due to a decrease in temperature during the shutdown leads to an increase in the hydraulic friction resistance forces and the pressure drop for pumping with a lower flow rate than before the shutdown. The oil temperature after 38 km from the beginning of the pipeline has a lower value than at the time of restart, so in the end of the pipe, the oil heating rate is less than its cooling rate (see Fig. 4).

The state of oil flow 12 hours after the restart of pipeline (see fig. 5) shows an increase in oil flow rate up to 931 t/h and oil temperature along the full length of pipeline due to the oil heating. The pressure drop on oil pumping is reduced due to the decrease in oil viscosity and hydraulic friction resistivity. The Fig. 6 shows the general change in the oil flow parameters after restart and transition to a steady-state mode.

The non-stationary process of the restart of pipeline after a short-term shutdown shows the change dynamics in the oil pressure and temperature during the transition of the flow parameters to the steady mode (see Fig. 6).

Conclusions

The calculation results show that the system of equations (1) - (5) of the mathematical model describes non-stationary processes of pipeline cooling and restarting after shutdown.

The calculated data allows determining the whole process of oil cooling for a given shutdown time for a given stop time, as well as pipeline starting by pumping units and preheaters with changing of state of oil flow parameters (velocity, pressure, temperature and viscosity)..

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Мұнай құбырының тоқтауы мен қайта қосылуын модельдеу

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ТҮЙІНДЕМЕ

Бұл мақала «Жетібай-Өзен» ыстық мұнай құбыры учаскесінің мысалында құбыр жұмысын тоқтату және қайта іске қосудың стационарлық емес процестерін модельдеуге арналған. Жылу-гидравликалық есептеудің математикалық моделі тасымалданатын мұнайдың реологиялық қасиеттерін ескере отырып берілген. Бұл есептеулер жұмыстың авторлары әзірлеген SmartTran бағдарламалық жасақтаманың арнайы модулімен орындалды. Есептеу нәтижелері құбырдың салқындауы кезінде мұнай температурасының уақыт бойынша төмендеуі және қайта іске қосылғаннан кейінгі құбырдағы мұнайдың қысымы, температурасы және жылдамдығы анықталды. Сондай-ақ, құбыр бөлігін қысқа аялдамадан соң қайта іске қосуға қажет сорғы қондырғыларының, қыздыру пештерінің пайдаланатын энергия қуаты бойынша нәтижелер алынды. Мұнай құбырының жұмысы тоқтағаннан кейін оның салқындауы және қайта іске қосу процестерін модельдеу мұнай айдау бекеттеріндегі сорғы қондырғыларының оңтайлы жұмыс режимдерін және құбырдың қауіпсіз тоқтау уақытын анықтауға мүмкіндік береді.

Түйін сөздер: мұнай құбыры, тасымалдау, тоқтату, қайта іске қосу, модельдеу, бағдарламалық жасақтама модулі.

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АННОТАЦИЯ

Статья посвящена моделированию нестационарных процессов остановки и перезапуска на примере «горячего» участка нефтепровода «Жетыбай-Узень». Приведена математическая модель тепло-гидравлического расчета с учетом реологических свойств транспортируемой нефти. Расчеты проведены специальным модулем программы SmartTran, разработанным авторами работы. В расчетах определены снижение по времени температуры нефти в трубопроводе при остывании и повышение давления, температуры, скорости нефти после перезапуска. Также получены данные по мощности насосных агрегатов, печей подогрева и потребляемой ими энергии, необходимой для перепуска участка трубопровода после краткосрочной остановки. Моделирование процессов остывания и перезапуска нефтепровода после остановки дает возможность подобрать оптимальные режимы работы насосных агрегатов на перекачивающих станциях и найти время безопасной остановки нефтепровода.

Ключевые слова: моделирование, нефтепровод, транспортировка, остановка, перезапуск, программный продукт.

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