

Comparison of measured and calculated high-viscosity crude oil temperature values in a pipeline during continuous pumping and shutdown modes

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ABSTRACT

The paper investigates the stationary and non-stationary cooling processes of high-viscosity crude oil temperature in the Severnye Buzachi – Karazhanbas pipeline during both pump operations and pump shutdowns. To transport high-viscosity crude oil through pipelines, the hot pumping method is employed. During oil transportation and pump shutdowns, the oil temperature decreases due to heat exchange with the environment, leading to an increase in oil viscosity. As viscosity rises, more power is required from the pumps to move the thickened oil, resulting in higher electricity consumption. To avoid increased operational costs after pump shutdowns, it is crucial to accurately calculate the oil cooling temperature in order to determine the safe shutdown duration and a critical temperature threshold. The Shukhov formula is used to calculate oil temperature during transportation, while a modified version is applied during pump shutdowns. To verify the accuracy of the obtained oil temperature results, the calculated values were compared with the measured values from pipeline sensors in both stationary and non-stationary cases. The novelty of the work is in determining the methodology for calculating the safe shutdown time of a pipeline for high-viscosity oil. The proposed formula was validated using experimental data from SCADA system sensors in real-time.

Introduction

Pipelines are often shutdown for scheduled maintenance, inspections, and pigging operations, as well as unplanned breakdowns caused by sudden issues such as oil spills, corrosion, ruptures, fatigue failure, power outages, or pump shutdowns due to hydraulic surges or transient pressures. After a hot oil pipeline shutdown, the oil temperature in the pipeline follows the Shukhov formula and decreases exponentially [1–5]. This cooling leads to a gradual increase in oil viscosity, which reduces flowability and significantly raises restart resistance. In more severe cases, deposits may form, causing blockages that can even lead to the shutdown of entire oil fields [6]. For instance, in the Valhall oil field in the Norwegian North Sea, wax deposition occurred in a subsea crude oil pipeline as the high-paraffin-content oil cooled below its cloud point of 26 °C, resulting in approximately 7500 barrels of solid wax accumulating in the pipeline by mid-1985 [7]. These cases illustrate how easily waxy and high-viscosity oils can deposit within pipelines, potentially leading to blockages due to changes in temperature and

pressure during production. If a hot oil pipeline becomes blocked or coagulates during shutdown, and the pressure required for restart exceeds the pipeline's structural limits, trenching the pipeline to clear the blockage may be necessary, causing significant operational delays and financial losses. For example, a 9 km surface oil pipeline in eastern Venezuela was completely blocked, with trenching and coiled-tubing used to clean out the pipeline, costing approximately USD 1.5 million and involving a highly complex process [8]. In 2009, the Zhongyin pipeline experienced a severe paraffin blockage between Daba Station and Yinchuan Station. To address this issue, trenching of the wax-plugged section was performed, along with the parallel installation of a bypass line. This method successfully restored the operation of the Zhongyin pipeline in 60 h [9].

In 2023, over 80 million tons of oil were transported through pipelines in Kazakhstan to oil refineries and foreign countries. Therefore, the continuous operation of pipelines plays an important role for the country's economy. High-viscosity oils of Kazakhstan have complex rheological properties, as a result of which complications arise during transportation through pipelines. To transport high-viscosity oils

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Nomenclature			
D_1	Pipe inner diameter, [m]	α_1	Internal heat transfer coefficient, [W/(m ² •°C)]
D_2	Pipe outer diameter, [m]	α_2	External heat transfer coefficient, [W/(m ² •°C)]
D_{ins}	Pipe insulation diameter, [m]	λ_{oil}	Oil thermal conductivity coefficient, [W/(m•°C)]
L	Pipe length, [m]	λ_{ins}	Thermal conductivity coefficient of the insulation layer, [W/(m•°C)]
H	Pipe laying depth, [m]	λ_{pipe}	Thermal conductivity coefficient of the pipeline, [W/(m•°C)]
T	Oil temperature, [°C]	λ_{soil}	Soil thermal conductivity, [W/(m•°C)]
T_{in}	Inlet oil temperature, [°C]	$\lambda_{oil(amb)}$	Oil thermal conductivity coefficient at ground temperature, [W/(m•°C)]
T_{soil}	Soil temperature, [°C]	Ins	Thermal resistances of the pipeline wall and insulation
T_x	Oil temperature at pipeline end, [°C]	t	Time, [s]
T_t	Change in oil temperature over time, [°C]	β_t	Oil volume expansion coefficient, [1/°C]
T_w	Average surrounding soil temperature, [°C]	ε	Paraffin content in oil composition, dimensionless
T_i	Initial value of paraffin formation temperature, [°C]	χ	Specific enthalpy of the phase transition of paraffin, [J/kg]
T_f	Final value of paraffin formation temperature, [°C]	g	Gravitational acceleration, 9.81 [m/s ²]
Q	Oil volumetric flow rate, [m ³ /s]	π	The ratio of a circle's circumference to its diameter, 3.14159
w	Oil velocity, [m s ⁻¹]	θ	Dimensionless parameter
ρ	Oil density, [kg m ⁻³]	Nu	Dimensionless Nusselt number
μ	Oil dynamic viscosity, [Pa•s]	Re	Dimensionless Reynolds number
ν	Oil kinematic viscosity, in [m ² /s]	Pr	Dimensionless Prandtl number
C_p	Oil apparent heat capacity, [J/(kg•°C)]	Pr_{av}	Dimensionless Prandtl number calculated at average temperature
C_s	Oil apparent heat capacity in solid phase, [J/(kg•°C)]	Gr	Dimensionless Grashof number
C_t	Oil apparent heat capacity in transition phase, [J/(kg•°C)]		
C_l	Oil apparent heat capacity in liquid phase, [J/(kg•°C)]		
k_1	Heat transfer coefficient from oil to the environment, [W/(m ² •°C)]		
k_2	Heat transfer coefficient for non-flowing oil, [W/(m ² •°C)]		

through the pipeline, the hot pumping method is applied. This method involves heating the oil using fired furnaces at heating stations and pumping the heated oil using pump units located at pumping stations. During pump shutdowns, oil flow through the pipeline stops, and hot oil no longer enters the pipeline. Temperature is one of the control parameters during hot oil pumping. The rheological properties of high-viscosity crude oil are highly dependent on temperature. Temperature distribution along the pipeline length depends on the heat transfer between the hot oil in the pipeline and the surrounding cold soil. The oil pipeline-soil system is in an unsteady state due to seasonal fluctuations in soil and air temperatures, changes in the properties of the surrounding soil and the rheological properties of the pumped oil. As the temperature decreases due to heat exchange with the environment, the high-viscosity crude oil thickens within the pipeline, eventually leading to a complete halt in pumping and substantial costs for restarting operations. The thickening of high-viscosity oil increases the pressure required for pipeline restart. Restart will fail if the flow pressure of the crude oil exceeds either the pipeline's maximum allowable operating pressure or the pump's maximum pressure capacity. As a result, the accident will cause great economic losses. To prevent oil from thickening, it is essential to determine a safe shutdown duration and critical temperature threshold by closely monitoring the oil's cooling process.

Economides [10] investigated the non-Newtonian behavior of Prudhoe Bay crude oil as it flowed through the Trans Alaska pipeline. Pseudoplastic behavior was observed at 1.67 °C and below, with waxing occurring at -30 °C. He calculated heat losses from the pipeline using transient temperature analysis, focusing on an unburied but insulated pipeline, with ambient temperatures ranging from -51 to 6.67 °C. His heat-transfer analysis predicted the cooling profile of trapped crude oil, with laboratory studies covering a temperature range of 60 to -29 °C. He also calculated the oil temperatures within the pipeline. Suleymanov [11] conducted calculations for a model pipeline under both continuous operation and shutdown scenarios using the PipeSim software. The model pipeline is 121 km long, with a diameter of 0.53 m and a burial depth of 0.8 m. The density of the transported oil is 800 kg m⁻³,

classified as very light crude oil with an API gravity of 44.8. The calculations covered both continuous and cyclic pipeline operations for various polyurethane insulation thicknesses on the pipe: 40 mm, 60 mm, and 80 mm. Initial oil temperatures of 40, 50, and 60 °C were set at the pipeline entry, with a safe cooling threshold of 9 °C. Suleymanov compared analytical calculation results with numerical simulations of oil cooling dynamics over a 4-day shutdown period between the Huludao station and the Suizhong station in China, obtained using the finite element method. The maximum temperature deviation between the two methods during the pipeline shutdown cooling period reached 22 %. Fugarov [12] analyzed the operation of a pipeline transporting hot oil through a horizontal route between two pumping stations, with pre-heating applied at the start of the section. The oil in the pipeline is medium crude with an API gravity of 30.6, flowing in a fully turbulent regime. This study focuses solely on theoretical models of steady-state operation, without experimental validation. Sukharev [13] conducted a computational experiment using a simplified model of an 80 km oil pipeline with an inner diameter of 700 mm, through which two successive batches of different oil grades were pumped. He applied distinct heat transfer coefficients to two 40 km segments of the pipeline: 3.5 W/(m•°C) for the first half and 1.5 W/(m•°C) for the second. This study primarily focuses on theoretical concepts and computational experiments. Markov [14] addressed the problem of determining the safe shutdown duration based on the time of year and the pipeline's operational duration. Reza [1] investigated the effects of temperature, flow rate, and oil characteristics in different pipeline diameters on Middle Eastern oil, which covers the largest oil reserves in the world, under Persian Gulf water conditions. He used the OLGA software package to model the pipeline in underwater conditions. Wang [15] studies the temperature drop of hot oil pipeline under buried pipes, above ground pipes and water pipes. Dongxu [2] studied the effects of flow rate and ambient temperature on crude oil using a heat-insulated experimental apparatus. Xu [16] simulated the temperature drop in a buried pipeline transporting hot crude oil during shutdown operation. He applied the finite volume method to model the temperature drop of the crude oil

during shutdown and obtained temperature profiles along both the radial and axial directions. Wei [17] developed mathematical models to analyze heat transfer behavior in oil pipelines during shutdown and restart operations, using finite difference and finite volume methods to solve the models numerically. Liu [18] modeled the temperature drop process in a buried hot oil pipeline. Xu [19] studied the heat transfer issues in long-distance pipelines under both operational and maintenance conditions. He developed a 3D mathematical model of heat transfer, accounting for the multifield coupling of atmosphere, soil, pipeline, and crude oil in both steady-state and shutdown modes. Lei [20] proposed a calculation model for simulating crude oil cooling during shutdown and restart processes, fully accounting for heat dissipation from the oil to the surrounding soil.

The Shukhov formula was used to determine the oil cooling temperature in the pipeline in studies [1–5,10–15]. Most research on oil transportation through pipelines focuses on waxy crude oil and the numerical solution for cooling hot oil within a two-dimensional domain over a short pipeline section or a pipeline cross-section [16–20]. Numerous researchers focus on the issue of heat transfer during pipeline operation and after shutdown, aiming to determine the drop in oil temperature within the pipeline and calculate the safe shutdown time [10–20]. In many studies, shutdown safety is evaluated by assessing the thermal conductivity of the soil surrounding the pipe.

The advantage of our work is a simplified method for determining safe shutdown time, which accounts for the heat transfer coefficient and incorporates the latent heat of phase transition through the heat capacity coefficient.

This article investigates the stationary and non-stationary cooling process of high-viscosity crude oil in the Severnyye Buzachi – Karazhanbas pipeline, which is located in the Mangystau Region, Kazakhstan.

Problem statement

The profile and location diagram of the Severnyye Buzachi – Karazhanbas pipeline are depicted in Fig. 1. The profile includes elevation points that are below or up to 30 m above sea level. The pipeline is situated in the Caspian Lowland, resulting in minimal variation in elevation points above sea level (see Fig. 1). The non-isothermal flow of high-viscosity oil flows from the Severnyye Buzachi station to the Karazhanbas station. The hot pumping method is carried out by the pumps at the Severnyye Buzachi station. Given the pipeline length of $L = 25,000$ m, which is significantly greater than the pipeline diameter of $D_1 = 0.414$ m, the problem is solved using a one-dimensional formulation.

The sensors of the SCADA (Supervisory control and data acquisition) system measure temperature, flow rate, and soil temperature in real-time (see Fig. 2).

When modeling the movement of oil through the pipeline, the equation for unsteady heat transfer of oil flow can be expressed as [21]:

$$\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - \frac{4k_1}{\rho D_1 C_p} (T_{in} - T_{soil}) \quad (1)$$

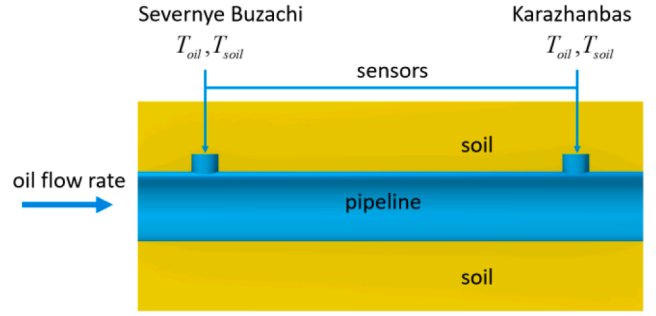


Fig. 2. Diagram of a buried pipeline with measurement sensors.

where T is the oil temperature, T_{in} is the oil temperature at the inlet, T_{soil} is the soil temperature, ρ is the oil density, C_p is the heat capacity, u is the oil velocity, k_1 is the heat transfer coefficient, D_1 is the pipeline internal diameter.

In the case of stationary pumping mode, Eq. (1) will be written in the form [22]:

$$\frac{\partial T}{\partial x} = -\frac{4k_1}{u\rho D_1 C_p} (T_{in} - T_{soil}) \quad (2)$$

From Eq. (2), the Shukhov formula is derived, which calculates the cooling of oil in the pipeline [1–5,10–15]:

$$T_x = T_{soil} + (T_{in} - T_{soil}) \exp\left(-\frac{k_1 \pi D_1 L}{Q\rho C_p}\right) \quad (3)$$

where Q is the oil volumetric flow rate, and T_x is the oil temperature at the end of the pipeline.

In Eqs. (1)–(3), the oil velocity, density, heat capacity, and volumetric flow rate are considered known based on the measurement data from the SCADA system.

The heat transfer coefficient of the pipeline is determined by the following factors: 1) the convective heat transfer of the oil flow from the pipe inner wall, 2) the thermal conductivity of the wall and insulation materials, and 3) the heat transfer from the outer surface of the pipeline to the environment (soil thermal conductivity) [23].

The heat transfer coefficient from the oil flow to the environment is expressed by the following formula [2,23]:

$$k_1 = \frac{1}{\frac{1}{\alpha_1} + D_1 \left(\frac{1}{2\lambda_{pipe}} \ln \frac{D_2}{D_1} + \frac{1}{2\lambda_{ins}} \ln \frac{D_{ins}}{D_2} \right) + \frac{D_1}{\alpha_2 D_{ins}}} \quad (4)$$

where D_2 is the pipeline outer diameter, D_{ins} is the pipeline insulation diameter, α_1 is the internal heat transfer coefficient from the oil flow to the pipeline inner wall, α_2 is the external heat transfer coefficient from the insulation surface to the environment, λ_{pipe} is the thermal conductivity coefficient of the pipeline wall, and λ_{ins} is the thermal conductivity coefficient of the insulation layer.



Fig. 1. Pipeline profile and station location diagram.

The soil thermal conductivity coefficient λ_{soil} is determined from expression (4) in such a way that the calculated oil temperature closely matches the oil temperature measured by the SCADA system.

The internal heat transfer coefficient α_1 from the oil to the pipeline wall is determined as [24,25]:

$$\alpha_1 = \frac{\lambda_{oil}}{D_1} Nu \quad (5)$$

where λ_{oil} is the oil thermal conductivity coefficient, Nu is the Nusselt number for heat transfer from the oil to the pipeline wall.

The Nusselt number is determined based on the Reynolds number [24]:

Laminar flow ($Re < 2000$):

$$Nu = 0.18 \cdot (Re)^{0.305} \cdot (Pr)^{0.42} \cdot (Gr)^{0.0931} \cdot (Pr_{av})^{-0.0218} \cdot (\theta)^{-0.071} \quad (6)$$

Transitional flow: ($2000 < Re < 5000$)

$$Nu = 5.86 \cdot 10^{-5} \cdot (Re)^{0.784} \cdot (Pr)^{0.422} \cdot (Gr)^{0.07} \cdot (Pr_{av})^{-0.0153} \cdot (\theta)^{0.05} \quad (7)$$

Transitional flow: ($5000 < Re < 10,000$)

$$Nu = 5.15 \cdot 10^{-5} \cdot (Re)^{1.418} \cdot (Pr)^{0.438} \cdot (Gr)^{0.018} \cdot (Pr_{av})^{-0.01} \cdot (\theta)^{0.00343} \quad (8)$$

Turbulent flow ($Re > 10,000$):

$$Nu = 0.021 \cdot (Re)^{0.8} \cdot (Pr)^{0.43} \quad (9)$$

where $Re = \frac{wD_1}{\nu}$ is the Reynolds number, $Pr = \frac{\mu C_p}{\lambda_{oil}}$ is the Prandtl number, $Gr = \frac{D^3 g \beta_t (T - T_{soil})}{\nu}$ is the Grashof number found at ambient (soil) temperature, Pr_{av} is the Prandtl number calculated at temperature $T_{av} = \frac{T + T_{soil}}{2}$, β_t is the oil volume expansion coefficient, $\theta = \frac{D_1}{\left(Ins + \frac{1}{\alpha_2}\right) \lambda_{oil(amb)}}$ is the

dimensionless parameter characterizing external heat transfer from the pipeline, $\lambda_{oil(amb)}$ is the oil thermal conductivity coefficient at ground temperature T_{soil} .

The value characterizing the sum of the thermal resistances of the pipeline wall and the insulation layer is expressed by the following formula:

$$Ins = \frac{D_1}{2\lambda_{pipe}} \ln\left(\frac{D_2}{D_1}\right) + \frac{D_1}{2\lambda_{ins}} \ln\left(\frac{D_{ins}}{D_1}\right) \quad (10)$$

The Forchheimer formula is used to calculate the external heat transfer coefficient [3–5,23]:

$$\alpha_2 = \frac{2\lambda_{soil}}{D_{ins} \ln \left[\frac{2H}{D_{ins}} + \sqrt{\left(\frac{2H}{D_{ins}}\right)^2 - 1} \right]} \quad (11)$$

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

Suppose at a certain point in time, oil pumping in the pipeline stops, initiating the cooling process of the non-flowing oil in the pipeline. In this case, the cooling process of oil in the pipeline in time can be described by the following equation:

$$T_t = T_{soil} + (T_{in} - T_{soil}) \exp\left(-\frac{4k_2 t}{\rho D_1 C_p}\right) \quad (12)$$

here, T_t is the change in oil temperature over time, and k_2 represents the heat transfer coefficient for non-flowing oil.

The heat transfer coefficient k_2 for non-flowing oil is expressed by the following formula:

$$k_2 = \frac{1}{D_1 \left(\frac{1}{2\lambda_{pipe}} \ln\left(\frac{D_2}{D_1}\right) + \frac{1}{2\lambda_{ins}} \ln\left(\frac{D_{ins}}{D_2}\right) \right) + \frac{D_1}{\alpha_2 D_{ins}}} \quad (13)$$

The heat capacity coefficient in formula (12) is calculated as follows. A decrease in oil temperature may cause the crystallization of paraffin contained in it, releasing the latent heat of the phase transition. The total amount of latent heat can be determined using the apparent heat capacity method [26,27].

$$C_p = \begin{cases} C_s & T < T_f \quad \text{solidphase} \\ C_t & T_f \leq T \leq T_i \quad \text{transitionphase} \\ C_l & T > T_i \quad \text{liquidphase} \end{cases} \quad (14)$$

where C_s , $C_t = \left\{ \int_{T_f}^{T_i} C_l(T) dt + \varepsilon \chi \right\} / (T_i - T_f)$, and C_l are the heat capacities in solid, transition, and liquid phases, T_i and T_f are the initial and final value of paraffin formation temperature, ε is the paraffin content in oil, χ is the specific enthalpy of the phase transition of paraffin.

The experimental data of the heat capacity $C_l(T)$ as a function of temperature is described by the empirical formula:

$$C_l(T) = (53357 + 107.2 \cdot T) / \sqrt{\rho_{20}} \quad (15)$$

By substituting $C_l(T)$ into C_b , oil apparent heat capacity in the paraffin crystallization zone can be determined.

Results

The SCADA system supplies essential real-time data for various parameters needed in the calculations. For this analysis, the pipeline segment between the Severnye Buzachi and Karazhanbas stations was examined.

The Severnye Buzachi oil blend is a high-viscosity oil, meaning it has a high resistance to flow [28]. This type of oil flows slowly and requires more energy for pumping and transportation. It is often classified as heavy oil and typically requires special techniques, such as heating, for extraction, transportation, and refining. At the Severnye Buzachi station, crude oil is heated in furnaces to 60 °C to reduce its viscosity, making it easier to transport. Once heated, the oil is pumped by the Severnye Buzachi station pumps toward the Karazhanbas station. During its 25 km journey through the pipeline, the oil gradually loses heat due to thermal exchange with the cooler surrounding soil, causing the temperature to drop progressively over the distance (Fig. 3). Fig. 3 illustrates the oil temperature, soil temperature, and flow rate from 18:00 on May 23, 2024, to 06:00 on June 10, 2024, over a total duration of 17 days and 12 h, or 408 h, during the oil transportation from the Severnye Buzachi station to the Karazhanbas station. The data is recorded every 30 min and stored in the SCADA system database. The figure shows a clear rise in soil temperature from May 23 to June 10, which can be attributed to the seasonal increase in ambient temperatures during the summer. As a result, the oil temperature at the Karazhanbas station also increases, reflecting the influence of the warming soil on the transported oil.

The data for the pipeline and the crude oil used in the calculations are presented in Table 1.

To calculate the cooling of high-viscosity crude oil temperature in the pipeline during continuous pumping mode, it is necessary to obtain oil viscosity dependence on temperature. The dependence of dynamic viscosity on temperature was obtained using a regression model, processing experimental data in the following form:

$$\mu(T) = 3.0676215 \cdot \exp(-0.0642764 \cdot T) \quad (16)$$

Once the relationship between dynamic viscosity and temperature is established, it becomes possible to calculate the internal heat transfer coefficient from the oil to the pipeline wall.

As illustrated in Fig. 4, the Severnye Buzachi oil blend exhibits the characteristics of high-viscosity crude oil, indicating that it is resistant to

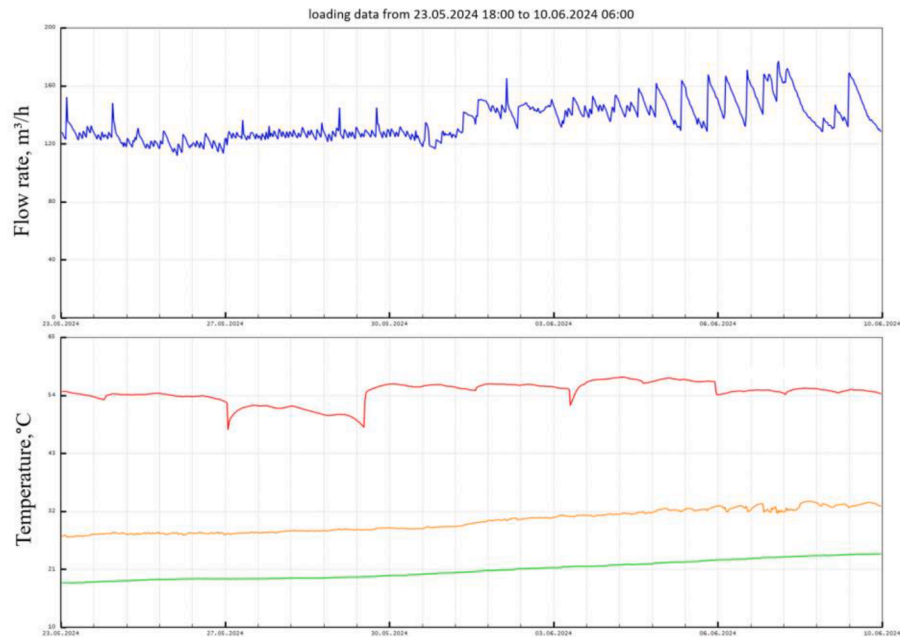


Fig. 3. Actual data from SCADA system sensors during oil transportation.

Table 1
Initial data for performing the calculations.

Parameter name	Designation	Value	Unit of measurement
Oil blend			
Density at 20 °C	ρ	938.9	kg m ⁻³
Thermal conductivity at 20 °C	λ_{oil}	0.144	W/(m•°C)
Specific heat capacity at 20 °C	C_p	1811	J/(kg•°C)
Volume expansion coefficient	β_t	0.000645	1/°C
Initial value of paraffin formation temperature	T_i	15	°C
Final value of paraffin formation temperature	T_f	5	°C
Paraffin content in oil	ε	0.18	
Specific enthalpy of the phase transition of paraffin	χ	220,000	[J/kg]
Pipeline			
Inner diameter	D_1	0.414	m
Outer diameter	D_2	0.426	m
Burial depth	H	1.207	m
Thermal conductivity of wall	λ_{pipe}	58.15	W/(m•°C)
Thermal conductivity of insulation	λ_{ins}	0.058	W/(m•°C)
Insulation thickness	δ_{ins}	0.0026	m
Length	L	25,000	m

flow and challenging to transport. With an API gravity of 18.9 and a specific gravity of 0.94, this oil blend falls within the category of heavy crude oil. These values signify that the Severnye Buzachi oil blend is denser and more viscous compared to lighter crude oils, which affects both its market value and the methods required for its extraction, transportation, and refining.

The thermal conductivity of soil in oil pipelines can vary significantly based on factors such as soil composition, moisture content, and temperature. In general, dry soil has a thermal conductivity ranging from 0.2 to 0.8 W/(m•°C), while moist soil ranges from 0.7 to 1.5 W/(m•°C). Saturated soil, such as clay or wet sand, has a higher thermal conductivity, typically between 1.5 and 3.0 W/(m•°C). The maximum soil thermal conductivity is around 3.0 W/(m•°C) for saturated soils like clay or wet sand, while the minimum soil thermal conductivity is about 0.2 W/(m•°C) for dry, loose soils like sand. These values are important in pipeline design because soil with higher thermal conductivity will

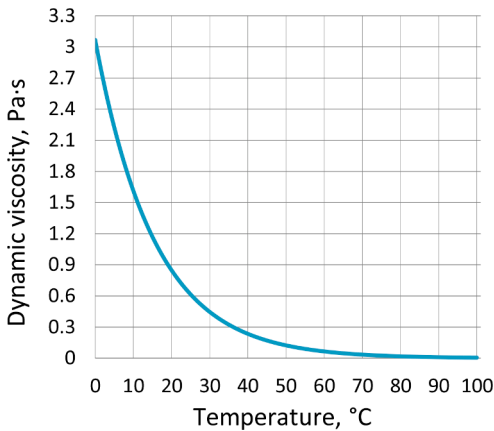


Fig. 4. Dynamic viscosity dependence on temperature.

transfer heat more efficiently, cooling the oil faster, while lower thermal conductivity will slow down the cooling process. In both stationary and non-stationary calculations, the maximum soil thermal conductivity was 1.503 W/(m•°C), while the minimum was 0.6 W/(m•°C).

The oil cooling calculations for the Severnye Buzachi – Karazhanbas pipeline were conducted under two distinct operating conditions: the continuous pumping mode, where oil is actively transported through the pipeline, and the pipeline shutdown mode, where the flow is halted, allowing researchers to observe how the temperature of the oil decreases over time. These calculations helped in understanding the heat transfer dynamics during both normal operational conditions and during temporary shutdowns, providing valuable data for optimizing pipeline performance and ensuring safe shutdown times to prevent increased oil viscosity and potential flow issues.

Figs. 5–6 illustrate the oil temperature drop during continuous pumping mode along the length of the Severnye Buzachi – Karazhanbas pipeline. The blue dots and lines show the calculated and measured oil temperature values along the pipeline length, while the green lines indicate the measured soil temperatures.

Fig. 5 illustrates the oil temperature distribution during stationary mode, captured at 07:30 on 15.02.2024. The measured oil temperature

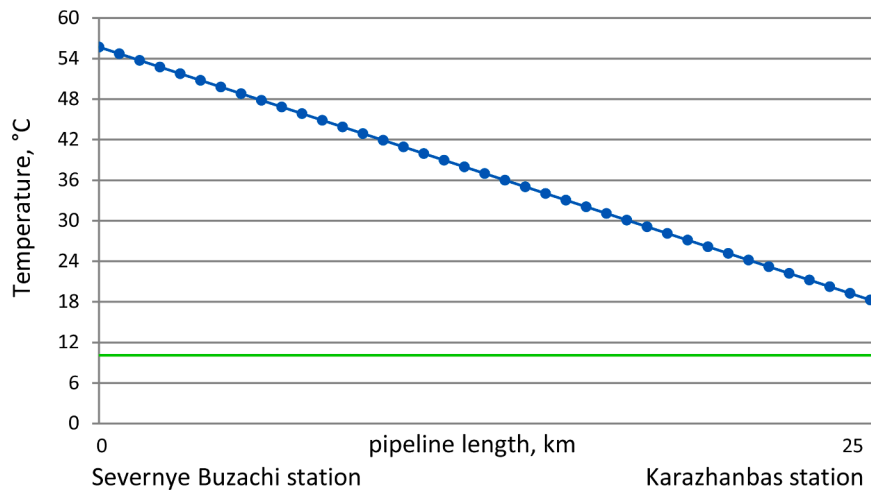


Fig. 5. Oil temperature distribution during stationary mode No 1.

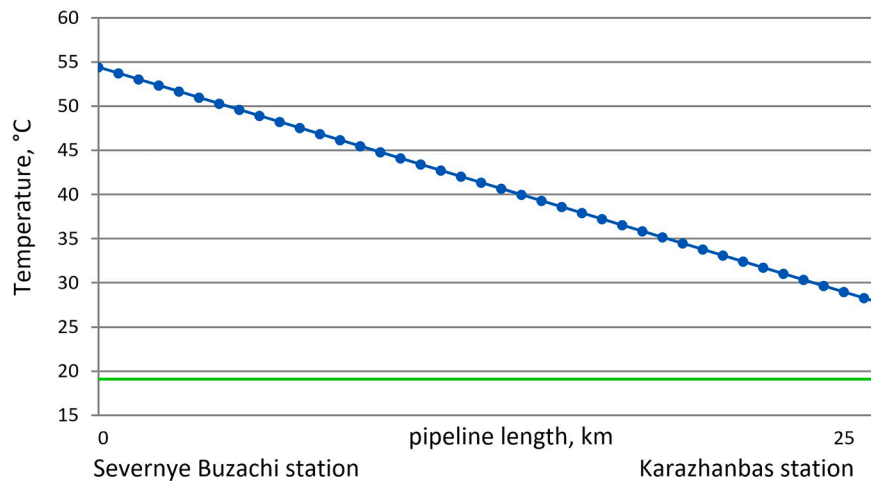


Fig. 6. Oil temperature distribution during stationary mode No 2.

is 55.7 °C at the Severnyye Buzachi station and 18.1 °C at the Karazhanbas station. The soil temperature is 10.1 °C. The oil flow rate is 99.2 m³/h. The soil thermal conductivity value is 1.38 W/(m•°C). The temperature difference between the calculated and measured data is 0.002 °C at the Karazhanbas station.

Fig. 6 shows the oil temperature distribution during stationary mode, recorded at 19:30 on 25.05.2024. The measured oil temperature is 54.4 °C at the Severnyye Buzachi station and 28 °C at the Karazhanbas station. The soil temperature is 19.1 °C. The oil flow rate is 119.2 m³/h. The soil thermal conductivity value is 1.5 W/(m•°C). The temperature difference between the calculated and measured data is 0.004 °C at the Karazhanbas station.

The calculated and measured values of oil temperature in stationary mode show a strong agreement, as illustrated in Figs. 5 and 6, indicating that the calculations align closely with the actual measurements and provide a reliable representation of the temperature behavior in the pipeline.

In stationary mode, the Shukhov formula accurately calculates the cooling of oil, and the calculated oil temperature values align closely with the measured data. However, in time-dependent mode, the calculated oil temperature during the cooling process after a pump shutdown may not align as well with the measured values. This discrepancy can be attributed to several factors, including sensor inaccuracies, power outages, and environmental influences such as rain, hailstorms, or snow, all of which can affect the reliability of the data. Therefore, the oil cooling

process following a pump shutdown was examined in greater detail, with more examples than in stationary mode. This was done to observe and analyze how the temperature drop occurs after shutdown, and to assess the reliability of the calculated results obtained using a modified version of the Shukhov formula.

During shutdowns of a "hot" pipeline, the heat from the heated oil gradually dissipates through the layers of insulation and the surrounding ground mass into the environment. As a result, the oil in the stopped pipeline cools down. As the temperature decreases, the properties of the oil begin to change, primarily its viscosity increases, and non-Newtonian properties start to manifest, which were not noticeable while the temperature remained sufficiently high. The oil may become so thick that additional energy is required to pump it, or it may even become nearly immobile without the application of heat. In the case of high-viscosity oil, prolonged stagnation can result in the need for much higher pressure to restart the pipeline, due to the greater resistance posed by the thickened oil. This increased demand on the system can strain pipeline infrastructure and pumps, potentially leading to equipment failure or expensive maintenance interventions. Restarting the flow after an extended shutdown can be very difficult or even impossible. However, during short-term shutdowns, that is, those not lasting too long, the parameters of these described phenomena do not reach dangerous levels. The heated ground has significant thermal inertia, allowing it to retain its insulating properties for an extended period, thereby preventing the oil in the pipeline from thickening.

The time interval is considered safe if, after its expiration, the resumption of pumping occurs without complications, i.e., friction losses (hydraulic resistance) do not exceed the pressure generated by the pumping station. The Severnye Buzachi – Karazhanbas pipeline allows for a safe shutdown duration of up to 72 h. This period is considered a safe window for performing repair work on the pipeline, as it provides sufficient time for workers to complete necessary maintenance tasks without compromising the integrity of the Severnye Buzachi oil blend or overall operation. Based on the actual data recorded by the SCADA system sensors, the minimum soil temperature in the Severnye Buzachi – Karazhanbas pipeline was 7.6 °C in 2020, 6.4 °C in 2021, 8 °C in 2022, 5.5 °C in 2023, and 7.6 °C in 2024. During the colder months (December, January, and February), the pipeline shutdown duration typically does not exceed 18 h and is generally limited to around 9 h. In contrast, during the warmer months, the shutdown duration can be extended due to higher ambient temperatures.

Another important point noted is that the oil temperature should not drop below 12 °C. While this is not critical, it is preferable to maintain the temperature above this threshold. As the temperature decreases, the oil viscosity increases, which in turn demands more power from the pumps and leads to higher energy consumption during transportation. In addition, the increased oil viscosity increases the load on both pipelines and pumps when pumping operations resume. The pressure generated by the pumping units must meet or exceed the hydraulic resistance of the pipeline section, but must remain below the maximum value allowed by the material strength of the pipes to ensure safe operation.

When a pipeline with a viscous product is stopped, when it cools down for more time than the safe pressure stop time, there are not enough units to push it out. In this case, the oil product is pushed out by low-viscosity products in sections. Along the pipeline route, linear wells with earthen barns are constructed every 5–15 km, and the frozen product is pushed out into them. To speed up the release of the pipeline, the pumps operate at maximum pressures.

The Severnye Buzachi – Karazhanbas pipeline was examined for instances of oil pumping stops. The oil supply shutdown was identified by a drop in flow rate of 0 m³/h in the actual archival data of the SCADA system (see Fig. 7). The graph illustrates the oil temperature, soil temperature, and flow rate from 15:30 on 09.05.2020 to 21:00 on

10.05.2020, covering a total period of 29.5 h. Additionally, the shutdown period is displayed from 21:00 on 09.05.2020 to 15:00 on 10.05.2020, spanning a total duration of 18 h. The blue line shows the flow rate at the Severnye Buzachi station. The red line represents the actual oil temperature values at the Severnye Buzachi station, while the orange line at the Karazhanbas station. The green line indicates the actual soil temperatures at the Karazhanbas station.

Figs. 8–12 show the measured and calculated oil cooling temperatures depending on the time after pumping was stopped in the Severnye Buzachi – Karazhanbas pipeline. The graphs show the cooling behavior of the oil based on the duration of the shutdown. The red line and dots represent the measured and calculated oil temperature values at the Severnye Buzachi station, while the orange line and dots represent those at the Karazhanbas station. The green line indicates the measured soil temperatures at the Karazhanbas station. The calculated oil temperature values are displayed in the figures above the measured temperature values for better understanding and visualization. Pipeline shutdowns are rare, and the measurement sensors sometimes display inaccurate data. The actual archived data from the Severnye Buzachi – Karazhanbas pipeline were observed from 2020 to 2024. Consequently, precise data from this period have been selected for analysis (see Figs. 8–12).

Fig. 8 shows a pump shutdown duration of 18 h, from May 9, 2020, at 21:00 to May 10, 2020, at 15:00. The maximum temperature difference between the calculated and actual data was 0.29 °C at the Severnye Buzachi station, where the soil thermal conductivity is 0.9 W/(m·°C), and 0.44 °C at the Karazhanbas station, where the soil thermal conductivity is 0.94 W/(m·°C).

In Fig. 9, the pump was shut down for 18 h, from 09:00 on 21.09.2021 to 03:00 on 22.09.2021. The maximum temperature difference between the calculated and actual data was 0.37 °C at the Severnye Buzachi station, where the soil thermal conductivity is 0.6 W/(m·°C), and 0.27 °C at the Karazhanbas station, where the soil thermal conductivity is 0.98 W/(m·°C).

In Fig. 10, the pump was shut down for 8.5 h, from 18:30 on 31.12.2021 to 03:00 on 01.01.2022. The maximum temperature difference between the calculated and actual data was 0.17 °C at the Severnye Buzachi station, where the soil thermal conductivity is 0.75 W/(m·°C), and 0.37 °C at the Karazhanbas station, where the soil

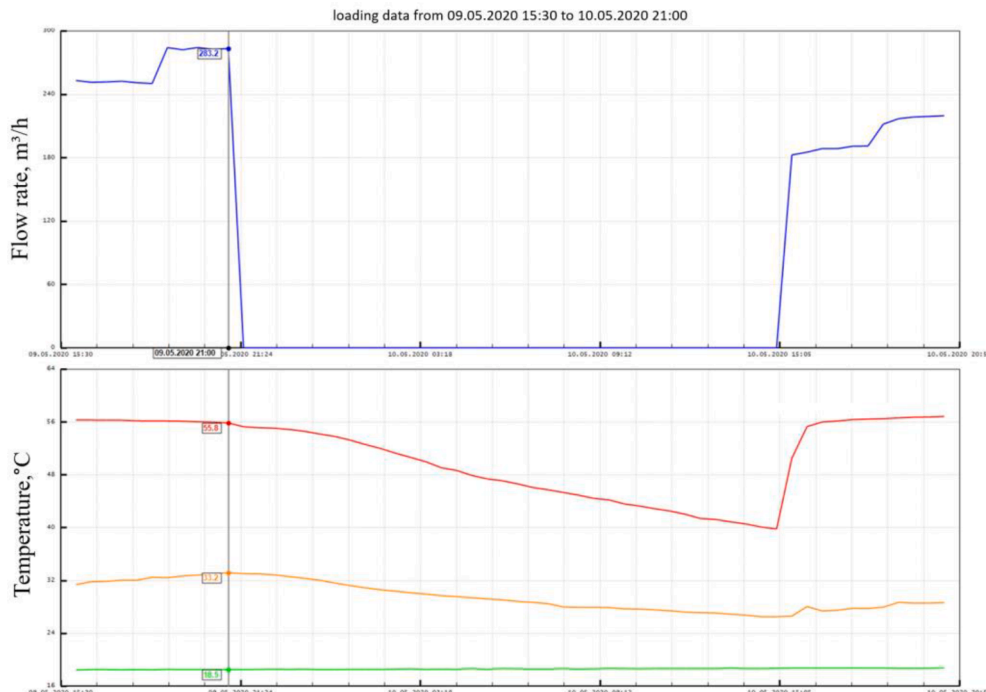


Fig. 7. Actual data from the SCADA system sensors during pump shutdown.

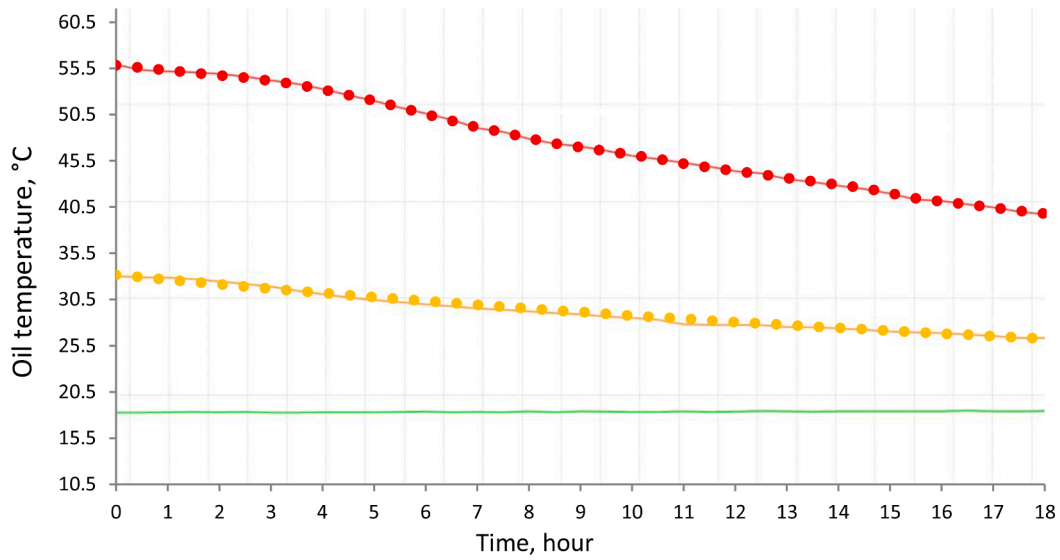


Fig. 8. Oil temperature drop after stopping oil pumping No 1.

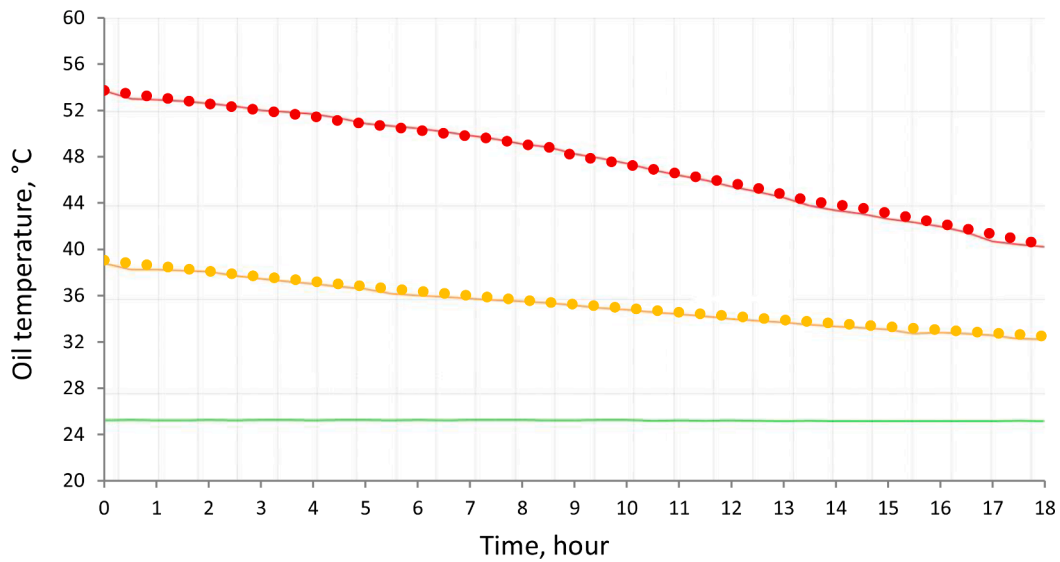


Fig. 9. Oil temperature drop after stopping oil pumping No 2.

thermal conductivity is $0.86 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$.

Fig. 11 illustrates a pump shutdown duration of 7.5 h, from October 31, 2023, at 19:30 to November 1, 2023, at 03:00. The maximum temperature difference between the calculated and actual data was 0.29°C at the Severnye Buzachi station, where the soil thermal conductivity is $0.9 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$, and 0.35°C at the Karazhanbas station, where the soil thermal conductivity is $1.0 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$.

Fig. 12 depicts a pump shutdown lasting 12.5 h, from 23:00 on July 12, 2024, to 11:30 on July 13, 2024. The maximum temperature difference between the calculated and actual data was 0.39°C at the Severnye Buzachi station, where the soil thermal conductivity is $0.65 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$, and 0.37°C at the Karazhanbas station, where the soil thermal conductivity is $1.35 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$.

The data presented in Figs. 8 to 12 illustrate that the temperature differences between the calculated and measured values during pump shutdowns are minimal, reflecting a high degree of accuracy in the temperature predictions. The maximum temperature difference observed across all examples ranged from 0.27°C to 0.44°C , with the largest discrepancies noted at the Karazhanbas station. These variations remained consistently small, regardless of the shutdown duration, which

varied between 7.5 h and 18 h. The results underscore the importance of soil thermal conductivity in influencing temperature dynamics. At both stations, differing conductivity values ranging from 0.6 to $1.35 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$ demonstrated how the thermal properties of the surrounding soil impact cooling rates. Overall, these findings affirm that the modified Shukhov formula provides reliable estimates for oil cooling during both short and extended pump shutdowns, which is essential for effective pipeline management and operational efficiency.

Conclusion

This study provides a comprehensive analysis of oil cooling behavior in the Severnye Buzachi – Karazhanbas pipeline under both continuous pumping and shutdown conditions, using the Shukhov formula and its modified version. The data demonstrated minimal temperature differences between calculated and measured values, with discrepancies ranging from 0.27°C to 0.44°C , affirming the high accuracy of the predictive models. The research highlights the critical role of soil thermal conductivity, which varied between $0.6 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$ and $1.5 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$. Shutdown durations, ranging from 7.5 to 18 h, showed that the

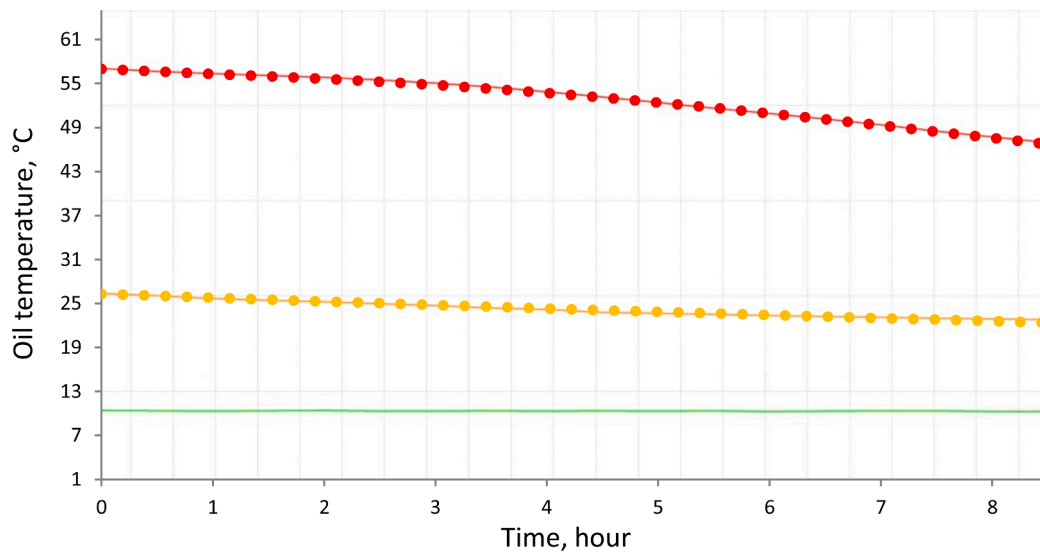


Fig. 10. Oil temperature drop after stopping oil pumping No 3.

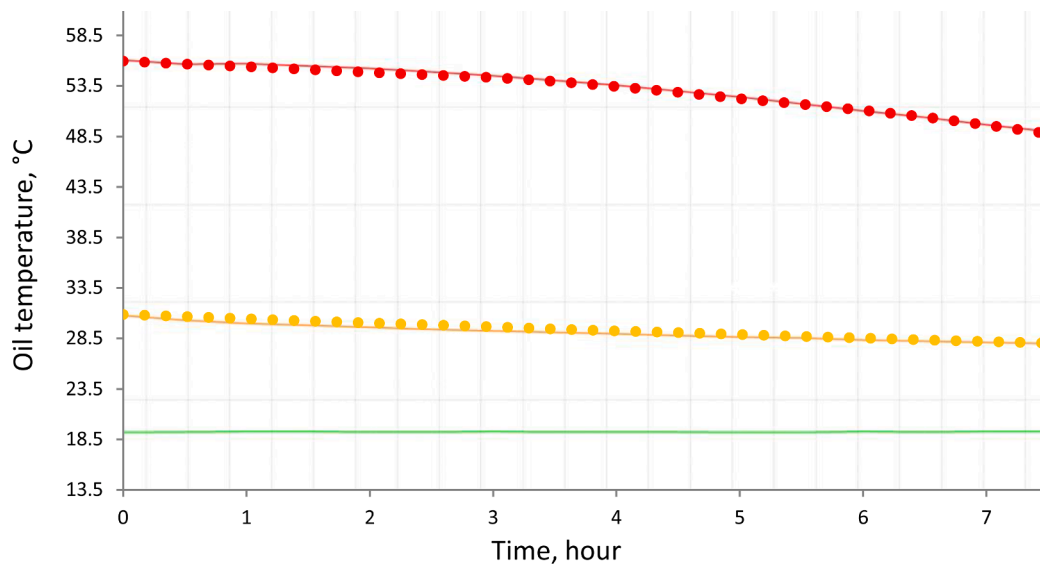


Fig. 11. Oil temperature drop after stopping oil pumping No 4.

modified Shukhov formula reliably estimates oil cooling, even in non-stationary conditions where factors like soil properties and environmental conditions influence results. Furthermore, the calculations underscore the importance of managing oil viscosity to prevent operational challenges during shutdowns. Extended shutdowns can lead to oil thickening, requiring higher energy to restart the pipeline, while short-term shutdowns remain manageable due to the thermal inertia of the surrounding soil. A key consideration when transporting high-viscosity oil is to prevent the oil temperature from falling below 12 °C. Although this temperature is not a strict limit, it is advisable to keep the oil above this threshold. As the temperature decreases, the viscosity of the oil rises, requiring more power from the pumps and significantly increasing energy consumption during transportation.

The calculation method presented in this paper allows for the determination of oil temperature in the pipeline by taking into account key factors such as pipeline parameters, oil properties, flow rate, temperature, and soil characteristics. In stationary mode, the Shukhov formula calculates the oil temperature values at any point along the length of the pipeline. The proposed mathematical model, derived from the modified Shukhov formula, allows for the accurate calculation of safe

shutdown times and critical temperature thresholds before pump shutdowns occur. This model determines how many hours are needed for the oil temperature to reach a specified level. Which, in turn, helps determine how many hours are available to perform repair work or other tasks without compromising the integrity of the oil blend or the overall operation.

This research offers valuable insights for pipeline operators, providing a solid foundation for optimizing shutdown times, ensuring safe maintenance procedures, and managing energy consumption. It also serves as a scientific reference for future studies on oil cooling in pipelines, particularly in scenarios involving high-viscosity crude oil. The findings are crucial for Kazakhstan and foreign oil transportation companies, which rely on the Shukhov formula for accurately predicting oil cooling temperatures, ensuring operational efficiency, and preventing potential flow issues.

CRedit authorship contribution statement

Daniyar Bossinov: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation.

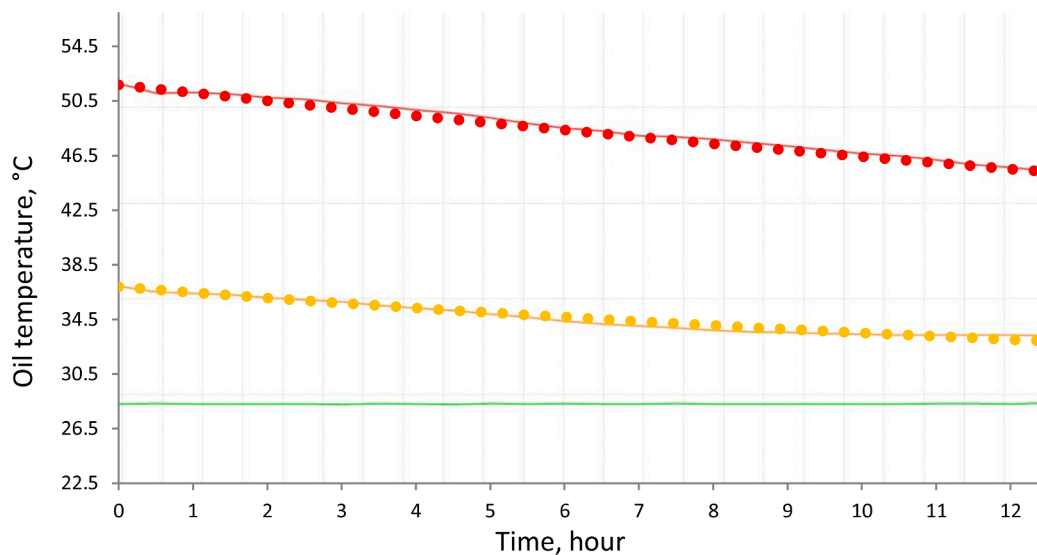


Fig. 12. Oil temperature drop after stopping oil pumping No 5.

Gaukhar Ramazanova: Visualization, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis. **Dinara Turalina:** Visualization, Validation, Resources, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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