

Calculation of High-Viscosity Oil Temperature During Pipeline Operation and Shutdown

Daniyar Bossinov*, Uzak Zhapbasbayev, Gaukhar Ramazanova

Satbayev University

Almaty, Kazakhstan

dansho.91@mail.ru

Abstract— The transportation of high-viscosity and waxy crude oils through long-distance pipelines presents significant thermal and hydraulic challenges, particularly when hot pumping is combined with temporary shutdowns. During normal operation, crude oil is heated to elevated temperatures to reduce viscosity and maintain stable flow. However, once pumping stops, the oil gradually cools due to heat exchange with the surrounding soil. This cooling leads to increased viscosity, higher restart pressures, and potential flow blockage caused by wax crystallization. Therefore, accurate prediction of temperature evolution under both steady-state and transient conditions is essential for ensuring safe and efficient pipeline operation. This study aims to determine how accurately the temperature behavior of high-viscosity crude oil can be predicted during both continuous operation and shutdown periods, and how these predictions can be used to estimate safe shutdown durations. In particular, the research investigates the influence of soil thermal properties, phase change effects, and flow conditions on cooling rates and restart constraints. The analysis is conducted for the Severnye Buzachi–Karazhanbas pipeline in the Mangystau region of Kazakhstan, which has a length of 25 km and an internal diameter of 0.414 m. The pipeline operates under hot pumping conditions, with crude oil heated to approximately 60 °C at the inlet. Due to the large length-to-diameter ratio, a one-dimensional heat transfer model is applied. For steady-state operation, the classical Shukhov formula is used to calculate the temperature distribution along the pipeline. During shutdown, a modified Shukhov-based approach is employed to describe transient cooling, accounting for heat exchange between the oil, pipe wall, insulation, and surrounding soil. The model includes variable heat transfer coefficients that depend on flow regime and material properties. To capture the effects of wax crystallization, the apparent heat capacity method is applied, incorporating latent heat into the thermal model. Oil viscosity is described as a function of temperature using a regression model based on experimental data. Validation is performed using operational data from a supervisory control and data acquisition system collected between 2020 and 2024. The simulation results show strong agreement with measured data. Under steady-state conditions, the temperature deviation at the pipeline outlet does not exceed 0.002 °C. During shutdown scenarios, the difference between calculated and observed temperatures ranges from 0.29 °C to 0.44 °C for shutdown duration 18 hours. The results indicate that soil thermal conductivity is a key factor governing the cooling rate of the pipeline. Higher conductivity leads to faster heat loss and reduced allowable shutdown times. The inclusion of latent heat significantly improves prediction accuracy by slowing the cooling process within the wax formation temperature range. These findings highlight the importance of considering both environmental and thermophysical factors in pipeline design and operation. The proposed modeling approach provides an accurate and physically consistent method for predicting temperature evolution in high-viscosity oil pipelines. It enables reliable estimation of safe shutdown durations and helps prevent operational failures associated with excessive cooling. The methodology can be applied to optimize pipeline operation and improve thermal management strategies in similar systems.

Keywords—non-isothermal flow, waxy oil, pump shutdown, safe shutdown time

I. INTRODUCTION

In 2023, over 80 million tons of oil were transported through pipelines in Kazakhstan to oil refineries and foreign countries [1]. Therefore, the continuous operation of pipelines plays an important role for the country's economy. Highly viscous and highly solidified oils of Kazakhstan have complex rheological properties, as a result of which complications arise during transportation through pipelines [2,3].

To transport highly viscous and highly solidified oils through the pipeline, the hot pumping method is applied [4-6]. This method involves heating the oil using fired furnaces at heating stations and pumping the heated oil using pump units located at pumping stations [7]. 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 waxy 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 waxy crude oil solidifies within the pipeline, leading to a complete halt of pumping and significant costs for restarting the operation [8,9]. To prevent this solidification, it is necessary to determine a safe shutdown time by monitoring the cooling temperature of the oil.

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

II. PROBLEM DEFINITION

The non-isothermal flow of waxy oil flows from the Severnye Buzachi station to the Karazhanbas station. The hot pumping method is carried out by the pumps at the Severnye Buzachi station. Given the pipeline length of $L = 25000$ m, which is significantly greater than the pipeline diameter of $D = 0.414$ m, the problem is solved using a one-dimensional formulation.

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

When modeling oil flow through the pipeline, the unsteady heat transfer of the oil can be described using the Shukhov formula [3-5]:

$$T_x = T_{soil} + (T_{in} - T_{soil}) e^{-\frac{k_1 \pi D_1 L}{Q \rho C_p}} \quad (1)$$

where T is the oil temperature at section x of the pipeline, T_{soil} is the soil temperature, ρ is the oil density, C_p is the heat capacity, w is the oil velocity, k_1 is the heat transfer coefficient, D_1 is the pipeline internal diameter, Q is the oil volumetric flow rate, T_{in} is the oil temperature at the inlet, and T_x is the oil temperature at the end of the pipeline.

The heat transfer coefficient from the oil flow to the environment (surrounding soil) is expressed by the following formula [7]:

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

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, and λ_{ins} is the thermal conductivity coefficient of the insulation.

The soil thermal conductivity 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 [7-9]:

$$\alpha_1 = \frac{\lambda_{oil}}{D_1} Nu \quad (3)$$

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 [8]:

Laminar flow ($Re < 2000$):

$$Nu = 0.18 \cdot (Re)^{0.305} \cdot (Pr)^{0.42} \cdot (Gr)^{0.0931} \cdot (Pr_{av})^{-0.0218} \cdot (\theta)^{-0.071} \quad (4)$$

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

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

Transitional flow: ($5000 < Re < 10000$)

$$Nu = 5.15 \cdot 10^{-5} \cdot (\text{Re})^{1.418} \cdot (\text{Pr})^{0.438} \cdot (\text{Gr})^{0.018} \cdot (\text{Pr}_{av})^{-0.01} \cdot (\theta)^{0.00343} \quad (6)$$

Turbulent flow ($\text{Re} > 10000$):

$$Nu = 0.021 \cdot (\text{Re})^{0.8} \cdot (\text{Pr})^{0.43} \quad (7)$$

where $\text{Re} = \frac{wD_1}{\nu}$ is the Reynolds number, $\text{Pr} = \frac{\mu \cdot C_p}{\lambda_H}$ is the Prandtl number, $\text{Gr} = \frac{D_1^3 g \beta_t (T - T_{soil})}{\nu}$ 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 coefficient of thermal expansion of oil, a is the thermal diffusivity coefficient,

$\theta = \frac{D_1}{\left(\text{Ins} + \frac{1}{\alpha_2} \right) \lambda_{oil(amb)}}$ is the dimensionless parameter characterizing external heat transfer from the pipeline,

$\lambda_{oils(amb)}$ is the oil thermal conductivity coefficient at ground temperature T_{soil} .

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

$$\text{Ins} = \frac{D_1}{2\lambda_{pipe}} \text{Ln} \left(\frac{D_2}{D_1} \right) + \frac{D_1}{2\lambda_{ins}} \text{Ln} \left(\frac{D_{ins}}{D_1} \right) \quad (8)$$

The thermal conductivity coefficients of pipeline wall λ_{pipe} and insulation λ_{ins} are taken from the SCADA system.

The Forchheimer formula is used to calculate the external heat transfer coefficient [7]:

$$\alpha_2 = \frac{2\lambda_{soil}}{D_{ins} \text{Ln} \left[\frac{2H}{D_{ins}} + \sqrt{\left(\frac{2H}{D_{ins}} \right)^2 - 1} \right]} \quad (9)$$

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 stationary oil in the pipeline. In this case, the cooling process of oil in the pipeline in time can be described by the following equation:

$$T_t = T_{soil} + (T_{in} - T_{soil}) \exp \left[-\frac{4k_2 t}{\rho D_1 C_p} \right] \quad (10)$$

here, T_t denotes the change in oil temperature over time, and k_2 represents the heat transfer coefficient for stationary oil.

The heat transfer coefficient k_2 for stationary oil is expressed by the following formula:

$$k_2 = \frac{1}{D_1 \left(\frac{1}{2\lambda_{pipe}} \text{Ln} \frac{D_2}{D_1} + \frac{1}{2\lambda_{ins}} \text{Ln} \frac{D_{ins}}{D_2} \right) + \frac{D_1}{\alpha_2 D_{ins}}} \quad (11)$$

III. RESULTS

The SCADA system provides the necessary actual values of various parameters required for the calculations. For the calculations, the pipeline section between the Severnye Buzachi and Karazhanbas stations was considered.

Figure 1 presents operational data spanning 17 days and 12 hours for the Severnye Buzachi to Karazhanbas pipeline, from 18:00 on May 23 to 06:00 on June 10, 2024. Recorded at 30-minute intervals by the SCADA system, the data include oil temperature, soil temperature, and flow rate. A steady increase in soil temperature is observed throughout the period, consistent with summer ambient warming. Consequently, the oil temperature measured at the Karazhanbas station exhibits a corresponding rise, demonstrating the direct thermal influence of the warming surrounding soil on the transported crude oil. The black line shows the flow

rate at the Severnye Buzachi station. The purple 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.

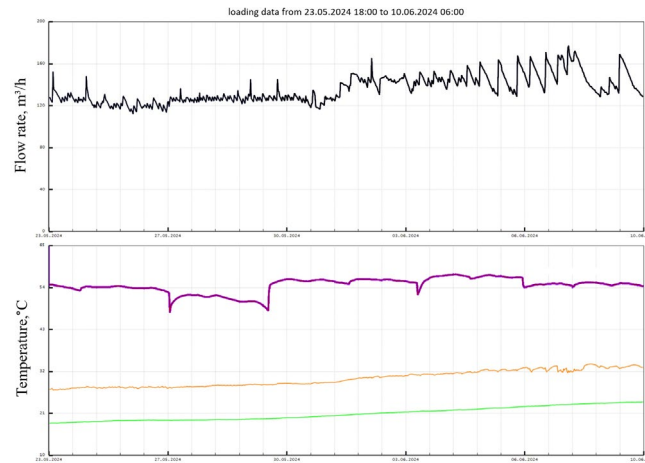


Fig. 1 Measured SCADA data during transportation

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. 2). 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 hours. 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 hours.

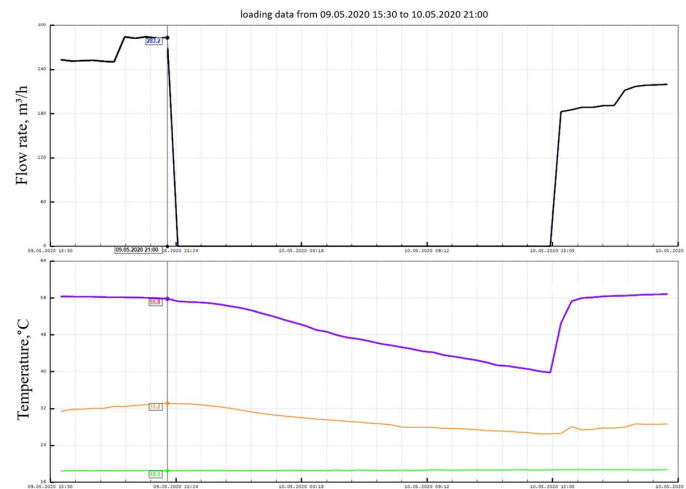


Fig. 2 Actual data of the SCADA system sensors

The oil blend has a density of 938.9 kg/m³, a thermal conductivity of 0.144 W/(m·°C), a specific heat capacity of 1808 J/(kg·°C) at 20°C, and a volumetric expansion coefficient of 0.000645 1/°C. The pipeline has an inner diameter of 0.414 m, an outer diameter of 0.426 m, a burial depth of 1.207 m, a wall thermal conductivity of 58.15 W/(m·°C), an insulation thermal conductivity of 0.058 W/(m·°C), an insulation thickness of 0.0026 m, and a total length of 25,000 m.

The dependence of dynamic viscosity on temperature was obtained using a regression model:

$$\mu(T) = 3.0676215 \cdot \exp(-0.0642764 \cdot T) \quad (2)$$

The oil cooling calculations were performed under two conditions: continuous pumping mode and pipeline shutdown mode.

Figure 3 illustrates the oil temperature drop during continuous pumping mode along the length of the Severnye Buzachi – Karazhanbas pipeline. The blue lines and dots show the calculated and measured oil temperature values along the pipeline length, while the green lines indicate the measured soil temperatures.

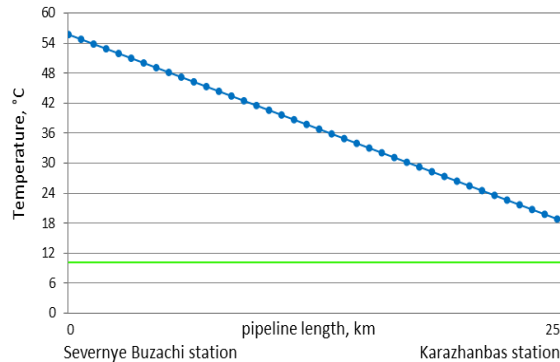


Fig. 3 Oil temperature distribution during stationary mode

Figure 3 shows the stationary oil temperature distribution as of 07:30 on 15.02.2024. Key data include an oil temperature of 55.7 °C at Severnye Buzachi and 18.1 °C at Karazhanbas, a soil temperature of 10.1 °C, a flow rate of 99.2 m³/h, and a soil thermal conductivity of 1.38 W/(m·°C). The calculated and measured temperatures at Karazhanbas differ by only 0.002 °C.

Figure 4 shows 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 lines and purple dots represent the calculated and measured oil temperature values at the Severnye Buzachi station, while the orange lines and blue dots represent those at the Karazhanbas station. The green lines indicate the measured soil temperatures.

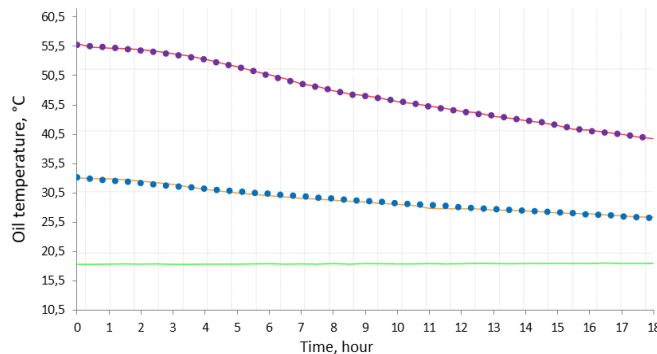


Fig. 4 Oil temperature distribution during stationary mode

Figure 4 presents a pump shutdown time of 18 hours, from 09.05.2020, at 21:00 to 10.05.2020, at 15:00. The maximum temperature difference between the calculated and measured 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).

IV. CONCLUSIONS

This paper presents mathematical models for determining the temperature drop of hot waxy crude oil in a buried pipeline during both continuous pumping and shutdown modes.

The calculated temperature values for continuous pumping and pipeline shutdown were compared with measured data from sensors along the Severnye Buzachi–Karazhanbas pipeline. The oil cooling calculations demonstrated that the calculated data for the Severnye Buzachi – Karazhanbas pipeline section align well with the measured data of the SCADA system. Both the Shukhov formula and its modified version allow for determining oil temperature during both stationary and non-stationary operating modes.

The study provides a scientific basis for accurately calculating safe shutdown times and managing oil pumping with variable shutdowns. The calculated results demonstrate that this method can accurately determine the temperature drop of highly viscous and highly solidified crude oil in a pipeline during shutdown.

ACKNOWLEDGMENT

This research was supported by the grant from Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP23486543 for 2024-2026).

REFERENCES

- [1] Ribeiro, F.S., Paulo, R.S.M., Sergio, L.B.: Obstruction of pipelines due to paraffin deposition during the flow of crude oils. *International Journal of Heat and Mass Transfer* 40(18), 4319–4328 (1997) [https://doi.org/10.1016/s0017-9310\(97\)00082-3](https://doi.org/10.1016/s0017-9310(97)00082-3)
- [2] Aiyejina, A., et al.: Wax formation in oil pipelines: a critical review. *International Journal of Multiphase Flow* 37(7), 671–694 (2011) <https://doi.org/10.1016/j.ijmultiphaseflow.2011.02.007>
- [3] Tugunov, P.I., Novoselov, V.F., Korshok, A.A.: Typical calculations for the design and operation of oil depots and oil pipelines. 2nd ed. Design-PoligraphService LLC, Ufa (2002)
- [4] Stepanov, O.A., Moiseev, B.V., Khopersky, G.G.: Heat supply at oil pipeline pumping stations. Nedra, Moscow (1988)
- [5] Novoselov, V.F., Korshak, A.A.: Pipeline transport of oil and gas. Pumping viscous and solidifying oils. Special pumping methods. Publishing house of the Ufa Petroleum Institute, Ufa (1988)
- [6] Beisembetov, I.K., Bekibayev, T.T., Zhabbasbayev, U.K., Makhmotov E.S., Kenzhaliev B.K.: Control of energy-saving modes of transportation of oil mixtures through main oil pipelines. KBTU, Almaty (2016)
- [7] Tonkoshkurov, B.A., Gostev, N.M., Shutov, A.A.: Methodology for thermal and hydraulic calculations of main pipelines under stationary and non-stationary modes of pumping Newtonian and non-Newtonian oils in various climatic conditions. All-Union Scientific Research Institute for the Collection, Preparation and Transportation of Oil and Petroleum Products, Ufa (1979)
- [8] Korshak, A.A., Pshenin, V.V.: New criterion equations for the Nusselt number during forced convection in pipes. *Notes of the Mining Institute* 195, 78–80 (2012)
- [9] Incropera, F.P., DeWitt, D.P.: *Fundamentals of heat and mass transfer*. 4th edn. John Wiley & Sons, Hoboken (1996)