Temperature condition of a stopped underground oil pipeline

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Abstract. Carrying out thermal calculations of “hot” oil pipelines, through which highly viscous and high pour point oils are transported, is one of the main ones. Determining the cooling rate of oil in a stopped oil pipeline is of great practical importance. The cooling time is used to calculate the safe stop time of the “hot” oil pipeline. The time at which there will be no freezing of the “hot” oil pipeline, and the station pressure is enough to overcome the shear stresses that arise when cooling highly viscous and high pour point oil. The methods of finding the cooling time of oil in a stopped pipeline are considered, which allow determining the time of a safe stop of the pipeline. Installed thermal stabilizers designed for cooling the soil can affect the cooling rate of the “hot” oil pipeline.

1. Introduction
Thermal calculation of the pipeline is an important task of pipeline transport to ensure reliability and safety, especially when laying in the Far North. [1,8,10-13] Since the majority of oil pipelines in Russia run in severe climatic conditions, the calculation of the rate of cooling of oil in the pipeline determines a safer time to stop it. With a long shutdown, highly viscous petroleum products can freeze, which will lead to significant economic costs. Thus, the correct calculation of the cooling time of oil and oil products allows one to determine the period during which the resumption of pumping will not have complications.

2. Object of study
Currently, there are several methods for determining the cooling time of oil in the pipeline. The thermal calculation of safe oil pipeline shutdown time, described in RD 39-30-139-79, was developed by Vadim Ivanovich Chernikin, Doctor of Technical Sciences, Professor. [2]

In this method, the heating process of the soil-pipeline system is determined to a greater extent by the rate of heating of the soil surrounding the pipeline. In turn, the heat of the oil product is neglected, since it is small relative to the heat accumulated in the soil. The soil surrounding the pipeline is considered to be isotropic with invariable physical constants. Thus, the process of cooling the oil product is due to the cooling rate of the soil.

The cooling process is characterized by the cooling rate or dimensionless temperature, determined by the following formula:

$$\theta = 1 - \frac{E_i(-h_0/R_2^2F_0) - E_i(-1/4F_0)}{2\ln(2h_0/R_2)}$$

where $E_i$ – sign of integral exponential function;
$h_0$ – pipeline laying depth, along the axis, m;
$R_2$ – outer pipeline radius, m;
$F_0$ – Fourier parameter calculated by the formula:
\[ F_0 = \frac{\alpha' T_{cool}}{R_2^2} \]  

(2)

where \( \alpha' \) – thermal diffusivity, m\(^2\)/s;

\( T_{cool} \) – duration of the pipe cooling process, s.

At \( h_0/R_2^2 \geq 4 \) the value \( E_i(-h_0^2/R_2^2 \cdot F_0) \) almost tends to zero. With this assumption, the formula will take the following form:

\[ \vartheta = 1 + \frac{E_i(-1/4F_0)}{\frac{2}{\ln(2h_0/R_2)}} \]  

(3)

When the pipeline cools down, the process of changing the temperature of the oil product along its length is described by the dependence:

\[ t = t_0 + \Theta (t_{in} - t_{fin}) e^{-Shu_l} \]  

(4)

where \( t_0 \) – ambient temperature around the pipeline;

\( t_{in} \) – initial fluid temperature;

\( t_{fin} \) – final fluid temperature;

\( Shu \) – Shukhov’s parameter;

\( l \) – current section length;

\( L \) – full section length.

If during a stop \( T_{ost} = 0 \), then \( \Theta = 1 \) and we have Shukhov’s law for the distribution of oil temperature along the length of the pipeline for stationary operation.

The value of the heat transfer coefficient from the pipe to the ground during cooling is described by the formula:

\[ a_2 = \frac{a_{2\infty}}{1 + 4F_0} \]  

(5)

where \( a_{2\infty} \) – heat transfer coefficient from the pipe to the ground in the outer surface of the pipeline to the environment during a stationary heat transfer mode, determined by the formula:

\[ a_{2\infty} = \frac{2\lambda_{cr}}{d_2 \ln \frac{h_0}{d_2}} \]  

(6)

where \( \lambda_{cr} \) – critical value of the thermal conductivity coefficient.

This formula is used only for \( h_0/D_2 \geq 3 \). With a smaller relative depth of laying, as well as with a depth of backfill of the pipe less than 0.7 m, it is necessary to take into account the thermal resistance at the soil - air boundary.

Another method is described in the book by Alexander Leonidovich Yastrebov "Engineering communications on permafrost soils." [3] When calculating the cooling time of the liquid in the pipeline, it was assumed that heat loss does not depend on the flow rate, since friction heat affects only at speeds greater than 2 m/s. The cooling time of the liquid during the underground laying of the pipeline will be calculated by the formula:

\[ \tau_{ost} = \frac{d_1^2 \gamma c}{8\lambda_{cr}} \ln \left( \frac{2h}{d_2} + \sqrt{\frac{4h^2}{d_2^2} - 1} \right) \ln \frac{\lambda_{cr} t_{fin} - \lambda_F t_{s}}{\lambda_{cr} t_{s} - \lambda_F t_{fin}}, \]  

(7)

where \( d_1 \) – internal diameter of the pipeline, m;

\( d_2 \) – outside diameter of the pipeline, m;

\( \lambda_{cr} \) – coefficient of thermal conductivity of thawed soil, kcal/h·deg;

\( \lambda_F \) – coefficient of thermal conductivity of frozen soil, kcal/h·deg;

\( t_s \) – soil temperature at the laying depth of the pipe axis, assuming that the pipe is absent, deg;

\( h \) – pipe laying depth from the surface, m;

\( \gamma \) – fluid volumetric weight, kg/m\(^3\);
c – specific heat of liquid, kcal/kg ∙ deg;

$t_{in}$ – initial fluid temperature before cooling begins, deg;

$t_{fin}$ – final fluid temperature, deg.

In the case when the pipeline has been working for a long time with a constant flow rate, a thawed zone will form around the pipe, and the adjacent frozen soil will be substantially warmed up. The cooling time of the liquid can be calculated using this formula:

$$\tau_{oct} = -\frac{\rho G w d}{24 \pi F T_s} \left[ \frac{(d_2+2\xi)^2}{d_2} - 1 \right] \ln \frac{6.8 h d_2}{d_2} - \frac{(d_2+2\xi)^2}{4d_2} \ln \left( \frac{(d_2+2\xi)^2}{d_2} \right),$$  \hspace{1cm} (8)

where $\rho = 80$ kcal/kg - heat of melting ice;

$\xi$ – thickness of thawed soil layer around the pipe, m;

$G_w$ – weight of water and ice per unit volume of soil, kg/m$^3$, determined by the formula:

$$G_w = \frac{W}{1+\gamma_0} \gamma_0,$$  \hspace{1cm} (9)

where $W$ – soil water content in fractions of a unit; $\gamma_0$ – volumetric weight of frozen soil, kg/m$^3$. In formula (8), the remaining notations are the same as in formula (7).

Formula (8) should be used when operating the pipeline for more than 5 years, provided that most of this time it works at a constant flow rate. For the initial period of operation of the pipeline or during its work with interruptions, formula (7) should be applied.

The considered basic methods for calculating the safe shutdown time of an underground oil pipeline have significant drawbacks. There are errors in the calculations using formula (1) with the results of experiments conducted on a pilot plant. Attempts have been made to compare the calculation results by the analytical formula with the results of numerical modeling [4], where differences were also obtained in solutions. The author of [4] obtained the estimated time intervals for safe shutdown of the pipeline which are less than the time allotted according to the plan for the elimination of possible accidents for facilities of the main pipeline, which provides for an increase in time by 30-50% depending on the complexity of the route.

It is necessary to refine the calculation formula to determine the time for safe shutdown of an underground oil pipeline. We will consider taking into account additional factors and parameters that may affect the cooling time of an underground oil pipeline.

Reliability of pipelines is laid at the design stage during calculations. Improving the calculation methods which will increase the accuracy of the results will ensure the reliability and safety of pipelines laid in the harsh climatic conditions of the Far North and the Arctic.

Oil product cooling in underground pipelines depends on the temperature of the soil around it. A “hot” stopped oil pipeline exchanges heat with the surrounding soil, which has not the best heat-conducting properties, and is close to insulators in terms of thermal conductivity [7]. The cooling process will take place due to the difference in temperature between the soil and the pipeline.

Installed thermal stabilizers designed to cool the soil to the design value [6] and maintain this state throughout the entire life cycle should affect the cooling rate of oil in the pipeline. As the heat stabilizers used for these purposes contribute to the additional cooling that the soil receives during the active period of operation — in winter [5]. The rate of hydrodynamic processes inside the device is much higher than the rate of temperature redistribution in the soil. Therefore, at negative atmospheric temperature, the thermal stabilizer will intensively cool the soil under the pipeline, which will affect the process and the cooling rate of oil.

3. Methods of study

In this work, a numerical experiment using modern mathematical modeling tools is carried out. Numerical modeling of the process of cooling oil in an underground oil pipeline was carried out using modern mathematical modeling tools.

The authors of the article proposed and implemented a calculation scheme: a model of a stopped oil pipeline with heated oil inside and a thermal stabilizer installed next to the oil pipeline in a two-
dimensional setting. According to the problem condition, the soil was set homogeneous, therefore, to
optimize the calculations, the model was divided into two symmetric parts and the symmetry condition
was set on the border in the Model tab. The model is shown in Figure 1.

\[ -\lambda \left( \frac{\partial T}{\partial n} \right)_{w} = q_{w}(x, y, z, t) = 0 \]

where \( w \)– normal to the surface of the body.

On the surface, a boundary condition is set - the interaction of soil with the atmosphere - taking into
account convective heat exchange with the atmosphere, the Heat Flow command.

\[ -\lambda \left( \frac{\partial T}{\partial n} \right)_{w} = q_{w}(x, y, z, t) \]

Also, the freezing power of the thermal stabilizer taking into account fluctuations in ambient
temperature will be taken into account. We set the boundary condition on the outer wall of the
evaporator, which is in contact with the soil according to the formula from [4]

\[ \frac{a_{c}S_{c}}{S_{ev}} \cdot (t_{a} - t_{g}) = -\lambda_{f} \cdot \left( \frac{\partial t}{\partial r} \right)_{R1} \]

where \( a_{c} \) – heat transfer coefficient from the condenser part;
\( S_{c} \) – condenser area;
\( S_{ev} \) – evaporator area;
\( t_{a} \) – air temperature;
\( t_{g} \) - temperature on the outer wall of the evaporator;
\( \lambda_{f} \) – soil thermal conductivity;
\( t \) – soil temperature depending on the radial coordinate \( r \) and time \( \tau \).

4. Results

When determining the safe shutdown time, the main step is to determine the cooling time of the oil
product in the underground pipeline. Existing methods do not allow taking into account all parameters
that may affect the cooling time. Oil product cooling in underground pipelines depends on the
temperature of the soil around it. The stopped oil pipeline exchanges heat with the surrounding soil, which has not the best heat-conducting properties, and is close to insulators in terms of the coefficient of thermal conductivity. The cooling process will take place due to the difference in temperature between the soil and the pipeline. It was discovered that the installed thermal stabilizers designed to prevent thawing of permafrost soil can affect the cooling time. During operation, soil thermal stabilizers freeze the soil adjacent to the underground oil pipeline, which receives a negative temperature and creates an additional temperature difference. Using the proposed formulas by the author and carrying out numerical modeling, using modern mathematical modeling tools, the process of cooling oil in an underground oil pipeline, it is possible to assess the degree of influence of the established thermal stabilizers on the cooling time of the oil product.

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