Mathematic simulation of the effect of a buried oil pipeline on permafrost soils

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Abstract. The paper is devoted to the study of the features of design and operation of main oil pipelines which run in the conditions of the Far North and places of permafrost soils distribution. The aim of the paper is developing of a mathematical model for the interaction of an underground oil pipeline in a multilayered concrete coated shell with permafrost soils, as well as a numerical solution of this model.

1. Introduction

At present, the geography of hydrocarbon production is changing, new fields of Eastern Siberia, the Far East, the Yamal Peninsula, the continental shelf of the Arctic seas are being developed according to the order of Government of Russia dated 13.11.2009 No. 1715-р "On the Energy Strategy of Russia for the period until 2030". The implementation of the strategy requires the design and construction of modern trunk oil pipelines for the transportation of hydrocarbons from production sites to domestic consumers under extremely unfavorable conditions [1].

Most of the above-mentioned territories refer to the places of permafrost soils distribution where the construction and operation of oil pipelines is hampered by unfavorable geo-cryological processes which can lead to a change in the design position of the pipeline and affect its reliability characteristics [2]. Therefore, even at the design stage, it is necessary to provide a set of protective measures to limit the impact of hazards within the limits which ensure reliable pipeline operation.

2. Methodology

The choice of technical measures to preserve the frozen condition of soils, preserve their temperature regime and ensure the reliability of the pipeline construction is made by calculation [3-6].

Data available for carrying out calculations are:

- climatic characteristics of the area;
- composition and temperature regime of the soil;
- technical characteristics of the pipe;
- physical and chemical parameters of the pumped product.

Under underground laying of oil pipelines, one of the main heat engineering calculations is the determination of heat losses. It causes a drop in product temperature, and as a result, a decrease in transport characteristics. The thermal losses at each section of the pipeline are determined by the formula:
\[ q = \pi k (t_v - t_n), \quad (1) \]

where \( k \) – coefficient of the heat transfer from oil to the soil, \( t_v \) – temperature of the pumped medium, \( t_n \) – temperature of the surrounding soil.

Heat transfer coefficient \( k \) shows the amount of heat passing from the oil product to the frozen soil through the pipe wall and layers of insulation coating and is calculated by the formula:

\[ k = \frac{1}{R}, \quad (2) \]

where \( R \) – thermal resistance of an isolated oil pipeline.

Thermal resistance is calculated for each layer of pipeline insulation coating:

\[ R = \frac{1}{\alpha_1 D_v} + \frac{1}{2\lambda_in \ln \frac{D_n}{D_v}} + \frac{1}{\alpha_2 D_n}, \quad (3) \]

where \( D_n, D_v \) – the outer and inner diameters of the insulation layer, m, respectively, \( \lambda_in \) - thermal conductivity of the insulating layer at an average insulation temperature W/m°C, \( \alpha_1 \) – coefficient of the heat transfer from the oil to the pipe wall W/m²°C, \( \alpha_2 \) - coefficient of the heat transfer from the surface of insulation to the soil W/m²°C.

Let us find the temperature of the surface of the wall of the underground oil pipeline:

\[ T_{ow} = t_n + \frac{q}{\alpha_2 \pi D_n} [K], \quad (4) \]

Based on the results obtained, when calculating the temperature on the final layer of insulation (Figure 1), it is necessary to simulate the effect of the heat flow on the frozen soil surrounding the pipeline.

![Figure 1](image)

**Figure 1.** Change in the wall temperature along the length of the pipeline.

To obtain the parameters of the thawing aureole in the permafrost, a mathematical model of the thermal interaction of the pipeline with a radius \( r \), buried to the depth \( H \) in the soil and describing there the heat exchange [7]. The choice of this model is due to the fact that the solution of the heat transfer problem in the soil in a two-dimensional formulation will increase the velocity of the predicted calculations [8].

Let us consider a multilayered monolithic oil pipeline laid in permafrost with soil temperature \( t = -4°C \) at the laying depth for the Nadym Region of the Yamal-Nenets Autonomous District.

To set and solve the problem, the following assumptions were made: the average depth of the pipeline in the soil from 1 to 1.8 m; the soil was presented in the form of a square section of the frozen area around the pipeline, considering the effect of outside air on the soil; the outside air temperature was constant and equal to -20°C [9]. Considering the above-described conditions, the design model of the process of heat distribution around the underground oil pipeline is presented in Figure 2.
Figure 2. Calculation model of the thermal interaction of an underground oil pipeline in permafrost soils: 1. steel pipe; 2. thermal insulation of the foamed polyurethane; 3. nano-modified concrete cover; 4. permafrost soil.

\[
C_{ef} \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial t}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial t}{\partial y} \right),
\]

where \( C_{ef} \) – effective heat capacity; \( t \) – soil temperature; \( \tau \) – estimated time.

Also, the effective heat capacity and the temperature range \( \Delta t \) is determined at which the ice-water phase transformations occur in the soil:

\[
C_{ef} = \begin{cases} 
C_{th}, & \text{when } t > t_f + \Delta t; \\
\rho c - \chi W(t) \frac{dt}{dt}, & \text{when } t \in [t_f - \Delta t, t_f + \Delta t]; \\
C_{fr}, & \text{when } t > t_f - \Delta t.
\end{cases}
\]

Where \( \rho \) - soil density; \( t_f \) – temperature of moisture transition; \( \chi \) - latent heat of phase transition; \( W \) – content of the non-frozen moisture; \( \gamma \) - specific gravity of the soil skeleton. The indices th and fr correspond to the thawing and frozen soil state:

\[
\lambda = \begin{cases} 
\lambda_{th}, & \text{when } t > t_f, \\
\lambda_{fr}, & \text{when } t \leq t_f.
\end{cases}
\]

Despite a fairly extensive set of precise analytical methods, many problems cannot be solved using them. Such problems are solved numerically. To solve the formulated model, the finite difference method was chosen. The calculation was performed in Excel and MATLAB & Simulink programs with subsequent verification (Figure 3).
Figure 3. Result of the thermo-technical calculation of a multilayered concrete coated pipe in permafrost soil.

The formulated mathematical model allows predicting a change in the temperature field around the buried oil pipeline with sufficient reliability, not only for a homogeneous soil, but also for soil layers with different thermal properties, to consider the change in the density of the soil skeleton as a function of temperature changes with a change in season as well as external factors (foundations of buildings and engineering communications) [10].

3. Conclusion

The implementation of predictive heat engineering calculations of the interaction of the buried oil pipeline with the permafrost soils is an important part of the design process, allowing making justified technical decisions aimed at increasing the reliability and lifetime of the facility.

A comprehensive approach to the selection of the best technical solutions, including the mathematical modeling of the thermal interaction of the pipe-ground system, allows minimizing costs without reducing the efficiency and reliability of the systems.

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