Complex thermophysical modeling of processes in the foundation soil of oil pipelines in the Arctic and offshore conditions

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Abstract. The paper presents the results describing the mathematical model in operation and testing methodology aimed at heat engineering calculations needed to do for multilayer oil pipelines. A section of the pipeline running under difficult geological conditions is under simulation. The methodology aimed at calculating the thermal processes and its results are described. The simulation was carried out by using some insulating materials with a constant internal diameter of the pipeline and a pumping mode. The simulation was carried out with the universal software system of end-element modeling – ANSYS and with a module developed by the authors for TPS thermotechnical calculations.

1. Introduction

In the modern world, where the production rate is increasing, the growing demands are made upon the construction and operation of oil and oil products transportation facilities. For this, the oil production zones are expanding, and more and more new fields are being developed; most of them are located in the northern part of Western Siberia and in the Arctic shelf.

Due to the extreme temperatures of these regions, some special requirements are made for the purposed technologies, constructions, necessary technical tools, as well as the production technological schemes, preparation methods, including the methods on recovery, storage and transportation of the hydrocarbon products.

For trouble-free operation of all of the above, it is needed to make a large number of calculations even at the development stage of all facilities involving in extraction and transportation of the oil products. The particular attention should be paid to pipeline networks laid in permafrost soil.

The pipelines laid in the permafrost soils have a number of serious problems that appear only after a sufficiently long period of time. All of them are associated with soil body thawing, which used to be in a frozen state. When thawing, soil characteristics begin to change, which entails a change in a pipeline design position, which leads to a change in a pipe geometry (deformation), a change in pumping conditions, and, as a consequence, to some accidents. It is also necessary to consider that all of the above also affect buildings and constructions located in the vicinity of the underground pipelines.

In view of the above, it seems relevant to develop a refined and effective methodology aimed at the thermal calculation of oil pipelines that will take into account the influence of heat transfer of oil and oil products on the environment. This method will enable to examine the effect of a pipeline on the permafrost soils of the Arctic zone and will allow to do more correct selection of material for laying [1-3].
2. Materials and methods
The thermal effect of the underground pipelines on the dynamics of seasonal soils freezing is determined by combination of many factors. The first group of the factors is: average annual, maximum and minimum temperatures of the transported product. The second natural factors are represented by some seasonal variations in air temperature. In other words, the set up task can be solved within the framework of a joint study of heat transfer processes inside a pipeline and in freezing soil with the conjugation of temperature and heat flux in a pipe-ground system.

The most complete mathematical model reflecting the processes of freezing and thawing in the moist soils in the continuous medium is the Stefan problem. The moving interface between zones with different aggregate states of pore moisture in the soil, which is not known in advance, puts the Stefan problem on a par with the most complex nonlinear problems solved by mathematical physics [4, 5].

At the first stage of the study, taking into account the above conditions, a calculation model of the heat distribution process around the underground oil pipeline was developed (Figure 1).

**Figure 1.** Calculation model of thermal interaction happening to underground oil pipeline in permafrost soils:
1. steel pipe; 2. thermal insulation of polyurethane foam; 3. nanomodified concrete coating; 4 permafrost soil.

The mathematical model of the thermal interaction of a pipeline with radius \( r \) buried to a depth \( H \) in the soil describes a heat transfer in the soil [6-8]:

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

(1)

where \( t \) is a temperature of soil;
\( \tau \) – estimate time.

Assuming that the phase transition of pore soil moisture occurs at a certain temperature range \( \Delta t_i \), effective heat capacity \( C_{ef} \) [9, 10]:

\[
c_{ef} = \begin{cases} 
  c_r, & \text{at } t > t_{ph} + \Delta t; \\
  \rho c_x - \chi \gamma \frac{dW(t)}{d\tau}, & \text{at } t \in [t_{ph} - \Delta t, t_{ph} + \Delta t], \\
  c_m, & \text{at } t > t_{ph} - \Delta t,
\end{cases}
\]

(2)

where \( t_{ph} \) is the temperature of the phase transition of moisture;
\( \chi \) – latent heat of the phase transition of moisture;
W – content of unfrozen moisture;
γ – the specific gravity of the soil skeleton;
ρₓ – the coefficient taking into account the density of the soil during subsidence of a pipeline.

The indices T and M correspond to the thawed and frozen state of the soil:

The second stage required verification of all previously described models in a program format to confirm the adequacy of the model. After working out the 3D model and designating all the necessary parameters and boundary conditions, a program was needed to choose. The choice focused on the program in which the simulation of the thermal processes as close as possible to the real conditions. It was the universal software system of end-element modeling – ANSYS [11].

The calculation of the parameters was carried out in the Transient Thermal package where a 2D model of the pipeline located in the soil body was loaded. In this calculation, the 2D model was used to speed up the calculations and minimize the computer-based load, and also this model allowed calculating a halo for a long time in the shortest possible time. To build up a more accurate calculation of the halo, the method of developing a triangular grid (Tetrahedrons) was used, and the cell size was adjusted (0.08 m), which will optimize the load in the calculation and obtain the correct data (Figure 2).

Figure 2. 2D soil model with the developed mathematical grid

The model also sets the parameters of the magnitude, type and properties of the materials and soils (thermal conductivity, density, specific heat) and the function of changing the temperature on the soil surface during a year was approximated (Figure 3) [12-14].

The last step before starting the calculation is to configure the solver of our thermal analysis model and select the boundary conditions in the program. In the Analysis Settings menu, the section Step-Controls, we set the time step for stationary thermal calculation. In the stationary calculation, time is used only to track the load history. The choice of a suitable time step value is very important because it affects the accuracy and stability of the solution:

• If the step is too small, oscillations can occur in the solution, which can lead to physically inadequate temperature values;
• If the step is too large, the temperature gradients may not be adequately resolved.

As an output, a small initial time step can be set up and the automatic selection function to increase the step size as far as possible can be used. To accurately determine the acceptable time step for our
problem, we use the Fourier number - this is a dimensionless time (∆t/t) that quantitatively determines
the ratio of thermal conductivity to stored heat for an element with a width ∆x: where r and c are the
average density and specific heat, respectively.

\[ F_o = \frac{4K\Delta t}{\rho C (\Delta x)^2} \] (3)

Next, the model is calculated by using all the boundary conditions and the solvers available in the
program for this type of calculation. After completing the calculation in this software package, it is
possible to display not only a graphic image of the temperature halo, but also graphs and various de-
pendences (Figure 4) [15].

![Figure 3. Schedule of temperature changes on soil surface during a year](image1)

![Figure 4. Graphic image of thawing ground halo](image2)

3. Conclusion
The values obtained as a result of modeling were compared with the data obtained by the authors in
the developed TPS software block based on Visual Basic for Applications (VBA). As a result, the data
discrepancy was 18%. At the moment, the modeling result is satisfactory. For a more accurate calculation, it is needed:

- to conduct additional soil studies in the Arctic zone;
- to clarify the grid on the model in the most important places;
- to verify the data of the author’s mathematical model.

Also, due to the mathematical modeling according to the developed methodology, we suggest that it is advisable to use multilayer concrete pipes in the most emergency sections in the Arctic region.

The developed mathematical model contains a large number of variables, including coefficients developed by the team of the authors under the guidance of Professor B.V. Moiseyev. These coefficients allow describing more accurately the processes taking place in the “pipe-soil” system over a sufficiently long period of time.

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