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## **Effect of Ice on the Heat-Moisture Regime of Soil Foundation** of Gas Pipeline

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Abstract. Operation of long-haul trunk pipelines in permafrost areas has shown that they undergo various negative processes, such as sweating, thermokarst, ice formation, etc. Especially in the mountainous areas, crossing the water barrier, in the wintertime ground is covered with ice. The interaction of pipelines with ice is not well researched. The purpose of this work is the numerical simulation of the heat-moisture regime of the soil base of the gas pipeline during the formation of ice. A mathematical model of heat and moisture transfer taking into account the actual process of freezing-thawing of the pore solution of soil is given. For mathematical modelling, a numerical experiment was performed to restore the heat flow of the icy valley using the method of solving boundary inverse heat conduction problems. As a result of a numerical experiment, it was established that the permafrost groundwater increases the average annual temperature of the soil around the pipeline and has a warming effect. During long-term operation of a gas pipeline with a positive temperature, the temperature of the soil base rises, but the thawing halo around the gas pipeline is small, which depends on the depth and thickness of pipe insulation.

#### **1. Introduction**

The Eastern Oil Pipeline (Eastern Siberia - Pacific Ocean pipeline system, ESPO) with a length of 4740 km was built in 2015, and the construction of the Power of Siberia gas pipeline will be completed at the end of 2019 (length is about 3000 km., Pipe diameter is 1420 mm, working pressure - 9.8 MPa, export capacity -38 billion cubic meters per year). The gas pipeline route passes through the territories of three constituent entities of the Russian Federation: the Irkutsk Region, the Republic of Sakha (Yakutia) and the Amur Region, in extreme climatic conditions, overcomes marshy, mountainous and seismically active territories, areas with permafrost and rocky soils. The absolute minimum air temperatures in the territory of the Power of Siberia gas pipeline are from minus 62°C in the Republic of Sakha (Yakutia) to minus 41°C in the Amur region.

During the construction of "Sila Sibiri" ("Power of Siberia"), Gazprom applies modern, highly reliable, energy-efficient technologies and equipment. In particular, Russian-made steel pipes with an internal smooth coating are used. This technology reduces energy costs for gas transportation by reducing the pipe roughness and, accordingly, friction. External insulation of pipes is made of innovative domestic nanocomposite materials and provides a high corrosion resistance of the pipeline.

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To cross the active tectonic faults, pipes with increased deformation capacity are used, as well as special technical solutions for their placement.

The design features and temperature conditions of pipelines depend on the nature of the product being pumped. Thus, oil pipelines can only be operated at a positive temperature, and the minimum oil pipeline temperatures are plus  $5-10^{\circ}$ C since the oil thickens at a lower temperature, paraffin plugs are formed, it becomes unsuitable for transportation. Gas pipelines can have both positive and negative temperatures.

Pipelines laid underground, have the greatest thermal effect on frozen soils since the main pipes lie in permafrost below the depth of seasonal thawing. Obviously, depending on the combination of the average annual, minimum monthly average, maximum monthly average gas temperature, the pattern of thermal interaction of the pipeline with frozen and thawed soils will be different. Thus, during the transportation of gas with a positive product temperature, perennial thawing halos will be formed during the entire period of operation in the areas of permafrost.

All this predetermines the specificity of geocryological studies in the design, construction and operation of main pipelines. The routes of the main pipelines are chosen in such a way as to bypass the areas with negative permafrost processes and phenomena (heaving bumps, active thermokarst, icing, stone runs, solifluction, etc.) (figure 1). Thermal insulation of the pipe is used to reduce the thermal interaction of hot and warm pipelines on the enclosing soils.



Figure 1. Negative processes in permafrost areas.

**Heaving.** At negative gas temperature, when freezing halos are formed around pipelines, they may bulge. The upper left figure (figure 1, A) shows the rise of the pipeline during frost heaving.

**Thermokarst and erosion.** The upper right figure (figure 1, B) shows the dynamics of erosion of strongly icy soils, while the clay soils of the slope are eroded, which enhances the thermokarst process.

**Karst soils**. ESPO and Power of Siberia are operated in a positive mode, the process of thawing permafrost is in progress, which strengthens karst processes. In the area of Olekminsk and Lensk, there are karst rocks (limestone, loam, sandy eluvial sandy loam, etc.). In some areas, the process of karst formation proceeds quite actively, with the pore water leaching soluble salts, which enhances the thermokarst process. In figure 2-3 shows the dynamics of the spread of salinity from the underlying carbonate layers during the operation of the pipeline with positive temperature. As a result of the thawing of carbonate soils, salt leaching occurs (leaching) and thermal subsidence of soil bases. To eliminate this process, ten-meter concrete piles and "chains" every 10 meters were used (figure 1, C).





**Figure 2.** Distributions of temperature (a), total moisture (b) and salinity (c) after 3 years. December.

**Figure 3.** Distributions of temperature (a), total moisture (b) and salinity (c) after 10 years. December.

In thermokarst areas, for example, insulating materials with different thicknesses are widely used to reduce the thawing depths and exclude precipitation and groundwater ingress. They replace karst rocks at the base of linear structures, lay high-strength and low-deformation geosynthetic materials.

Aufeis (figure 1, D), which arises and grows only in the frosty period of the year, is formed by various waters: underground, river and lake (often ice dams have mixed feeds) [1-3]. When they repeatedly erupt on the surface and layer-by-layer freezing, flat-convex ice bodies are formed – ice. Aufeis affects the redistribution of surface runoff, affect the relief and cause the formation of specific sediments ("icy alluvium"), which have a negative impact on engineering structures.

The interaction of trunk pipelines with ice is not well understood. In Yakutia, ice formation processes are mainly concentrated in river basins with mountainous terrain. In this paper, we consider how frost formation affects the heat and mass transfer regime of a soil base of a gas pipeline. The purpose of this work is the numerical simulation of the heat-moisture regime of the soil base of the gas pipeline during the formation of ice.

#### 2. Problem statement and solution algorithm

The mathematical model of heat and moisture transfer (in vertical section) in freezing-thawing frozen soils is described by the following system of equations [4]:

$$c\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) - c_g \left( V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} \right) + L \frac{\partial W_x}{\partial \tau}, \tag{1}$$

$$\frac{\partial \theta_{e}}{\partial \tau} = \frac{\partial}{\partial x} \left( k_{\phi} \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{\phi} \frac{\partial H}{\partial y} \right) - \frac{\partial \theta_{\pi}}{\partial \tau}, \tag{2}$$

$$\frac{\partial W_{e}}{\partial \tau} = \frac{\partial}{\partial x} \left( k \frac{\partial W_{e}}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial W_{e}}{\partial y} \right) - \frac{\partial k_{\phi}}{\partial y} - \frac{\partial W_{\pi}}{\partial \tau}$$
(2\*)

 $(x, y) \in \Omega, \quad \tau > 0, \qquad \Omega = [0, R] * [0, H].$ 

The system of equations  $(1) - (2^*)$  is closed by the equation for the amount of unfrozen water [3]:

$$W_{H\theta} = W_{H\theta}(T, W) \tag{3}$$

Equation (1) takes into account the process of freezing-thawing of the pore solution (water) with filtration. The movements of the pore solution itself, taking into account the ice release, are described by a similar equation of parabolic type (2) and ( $2^*$ ). Equation (2) is the Richards equation and is used in saturated media, and expression ( $2^*$ ) is unsaturated.

The two-dimensional numerical simulation area is a vertical section of the ground with coordinates (x, y). On the soil surface (upper boundary), the boundary conditions of the second kind for temperature and the condition for the infiltration of precipitation or evaporation are set:

$$-\lambda \frac{\partial T}{\partial z} = q(\tau), \quad y = 0, \quad 0 < \tau \le \tau_m,$$
(4)

$$-k\frac{\partial W}{\partial \tau} = q_{W}(\tau)$$
(5)

At the base is the boundary condition of non-flowing, and on the left and right borders of the region the inflow and removal of permafrost seasonal groundwater are set.

The condition of thermal conductivity is set on the pipeline wall [4]:

$$\lambda \frac{\partial T}{\partial n} = Q(\tau) \tag{6}$$

Heat transfer through the pipe walls during forced turbulent movement of the transported product is described as follows:

$$Q(\tau) = \alpha (T_{\Gamma} - T), \tag{7}$$

where  $\alpha = Nu\lambda_{\text{III}}/d$  – heat transfer coefficient.

Here  $c, c_{\rm B}$  – bulk heat capacity of soil and water, J/(m<sup>3</sup>·K);  $\lambda$  – thermal conductivity, W/(m·K); T – temperature, K;  $\tau$  – time, s; L – phase transition heat, J/m<sup>3</sup>; W = W<sub>l</sub> + W<sub>h</sub> – total moisture weight, in the form of ice and water, %;  $\theta = \theta_l + \theta_h$  – total bulk humidity, bulk ice content, water, % ; H = P - y – water pressure, m ; P – soil suction pressure in water column, m; k – diffusion coefficient, m<sup>2</sup>/s; C<sub>f</sub> – filtration coefficient, m/s; V = (V<sub>x</sub>, V<sub>y</sub>) – groundwater velocity vector; x, y – spatial coordinates (y – vertical axis downward), m; n – outward normal; R, H – width and depth of

the area under consideration, m;  $\lambda_{pr}$  – width and depth of the area under consideration, W/(m·K); d – pipe diameter, m; Nu – Nusselt number.

In the area under consideration, taking into account the location of the main pipeline, a discrete non-uniform grid was introduced along the x, y coordinates and a uniform time step. The heat equation contains convective terms, which can be represented in non-divergent (non-conservative) and divergent (conservative) forms. It should be noted that schemes with directed differences are widely used in practice for convective terms, taking into account the sign of the filtration rate [5].

The system of equations was approximated by an implicit difference scheme for a chain of onedimensional non-linear problems [4, 5]:

$$\begin{cases} c_{ef}T_{\overline{\tau}} + D_{1}T + c_{h}C_{1}T = \varphi_{1}, \\ W_{\overline{\tau}} + D_{2}W = \varphi_{2}, \\ \mu_{i}^{s} \frac{P_{i}^{s+1} - P_{i}^{s}}{\tau} + \frac{\theta_{i}^{s} - \overline{\theta}_{i}}{\tau} + D_{3}P = \varphi_{3} \end{cases}$$

Here  $D_1, D_2, D_3$  – difference operators,  $c_{ef}, c_h, \mu_i^s, \varphi_1, \varphi_2, \varphi_3$  – difference analogs of the coefficients.

$$C_1 T = (V^T T_r + V^T T_{\bar{r}}),$$

where  $V = V^+ + V^-$ ,  $V^+ = 0.5(V + |V|) \ge 0$ ,  $V^- = 0.5(V - |V|) \le 0$ .

Numerical implementation of a nonlinear difference problem is carried out using iteration.

#### 3. Numerical experiment

The initial parameters for the computational experiment on heat and moisture transfer at the base of the gas pipeline were determined in relation to the climatic conditions of Central Yakutia. The gas pipeline with a diameter of 1400 mm is laid at a depth of 2.4 m. The temperature of the transported gas depends on the operating conditions and at the beginning of construction is equal to the temperature of the adjacent soil, and then gradually turns into a positive mode of operation.

On the surface of the soil we set the boundary condition of the second kind. When calculating, the recovered heat flux densities [6] are used, which take into account the thickness of the ice massif. The height of the ice is two meters, but every year it changes depending on the external temperature and the volume of groundwater. From about October to December the ground is covered with snow, and from January to July – with ice.

The soil lithology for model numerical calculation is selected according to engineering survey data (table 1). In mountainous areas, as a third layer (gravelly sand), bedrock rocks such as granite, limestone, gneiss, dolomite, etc., are found [7–9].

Soil type	Layer depth, m	Skeleton bulk density <b>r</b> , kg/m <sup>3</sup>	Thermal conductivity, W/(m·C)		Specific heat,	Saturation humidity,
			$1_{\mathrm{T}}$	l <sub>M</sub>	J/(Kg-K)	%
Topsoil	0.0-0.1	700	0.59	1.40	550	15
Coarse sand	0.1-1.4	1400	2.15	2.67	690	20
Gravel sand	1.4	1500	2.25	2.70	690	25

Table 1. Thermo physical characteristics of ground.





**Figure 4.** Distributions of temperature (A, B) and total humidity (C, D) in June.

**Figure 5.** Distributions of temperature (A, B) and total humidity (C, D) in September.

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**Figure 6a.** Temperature distribution with positive operation and in the presence of permafrost water flow.

**Figure 6b.** Distribution of total humidity with a positive mode of operation and in the presence of permafrost water flow.

13,3

16,7 20,0

3,3

6,7 10,0

0,0

1 year

10.0 13.3

5 years

10 years

0.0 3.3 6.7

0,0 3,3 6,7 10,0 13,3 16,7 20,0

32

32

16.7 20.0

32 25

#### 3.1. The results of a numerical experiment

With the onset of the warm period, melting of ice occurs. Numerical studies show that the thawing intensity depends on the external temperature and ice area, and sometimes ends at the end of July or does not completely thaw. The depth of seasonal thawing in comparison with the control platform is late (figure 4, 5). Thawing of ice occurs simultaneously with the admission of permafrost groundwater, which enhances the thawing process.

During long-term operation of a gas pipeline with a positive temperature, the temperature of the soil base increases, but the thawing halo around the gas pipeline is small (figure 6a). The main gas pipeline is located on the active layer (the pipe axis is at a depth of 1.7 m) and the average annual negative ambient temperature ( $-8^{\circ}$ C) suppresses the positive temperature of the pipe. In this case, the pipeline is located across the flow of superfrost groundwater and blocks their flow (figure 6b).

#### 4. Conclusion

As a result of a numerical experiment, it was established that the formation of ice occurs in the second half of winter and has a warming effect. In the first half of the summer period, intensive thawing of ice

is observed, and the dynamics of the depth of seasonal thawing come with some delay, but at the beginning of the winter period, it is restored, as in ordinary soil.

During long-term operation of a gas pipeline with a positive temperature, the temperature of the soil foundation rises, but the thawing halo around the gas pipeline is small.

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