Simulation of long-term influence from technical systems on permafrost with various short-scale and hourly operation modes in Arctic region

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Simulation of long-term influence from technical systems on permafrost with various short-scale and hourly operation modes in Arctic region

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Abstract.
Technogenic and climatic influences have a significant impact on the degradation of permafrost. Long-term forecasts of such changes during long-time periods have to be taken into account in the oil and gas and construction industries in view to development the Arctic and Subarctic regions. There are considered constantly operating technical systems (for example, oil and gas wells) that affect changes in permafrost, as well as the technical systems that have a short-term impact on permafrost (for example, flare systems for emergency flaring of associated gas). The second type of technical systems is rather complex for simulation, since it is required to reserve both short and long-scales in computations with variable time steps describing the complex technological processes. The main attention is paid to the simulation of long-term influence on the permafrost from the second type of the technical systems.

INTRODUCTION

Permafrost occupies about 25% of the world's land area. Development of mathematical models of the interaction of permafrost with a changing climate system and study of the long-term influence of climatic factors on the dynamics of permafrost degradation is an actual problem [1, 2]. Changes in permafrost are also related to human activities [3]. For example, the exploitation of northern oil and gas fields has a major impact on the processes of permafrost degradation [4]. The main sources of heat in the frozen ground are various technical systems used in oil and gas fields [5, 6, 7, 8].

An important task is to minimize the thermal interaction in a "heat source–permafrost" system. Therefore, it is necessary to take into account parameters of used thermal insulation [9] and possible devices used for thermal stabilization (cooling) of the soil such as seasonal cooling devices, as in [10, 11].

According to the paper [8] a mathematical model is suggested for long-time forecasting of impacts of development and exploitation of a flare pad located in areas of permafrost. The developed numerical methods for solving various problems associated with simulation of non-stationary thermal fields in frozen ground can also be used to solve geothermal problems taking into account their specific features [12, 13].

In this paper a problem related to simulation of thermal effect of a horizontal flare system operation on the degradation of permafrost is considered. The specificity of this problem is that unlike the previously considered heat sources, the simulated system does not work over the entire simulated time interval of the flare system operation, but only for a short time when an accidental discharge of the flared gas occurs. At the same time, these time intervals of this system can be repeated, which makes certain numerical difficulties for long-term simulation of such systems.

MATHEMATICAL MODEL

Simulation of thermal processes related with different engineering constructions operating in a permafrost zone are based on the natural temperature fields forming. Essential climatic factors are the soil ground temperature, air temperature, and solar radiation. In Figure 1 these parameters are presented for a zone to be considered. The initial temperature
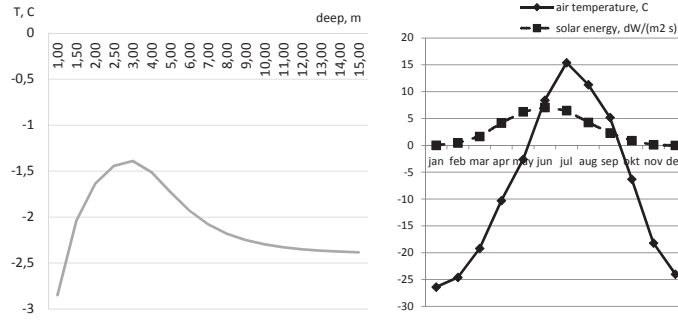
FIGURE 1. Vertical temperature profile in soil on October (left). Annual air temperature and solar energy (right).
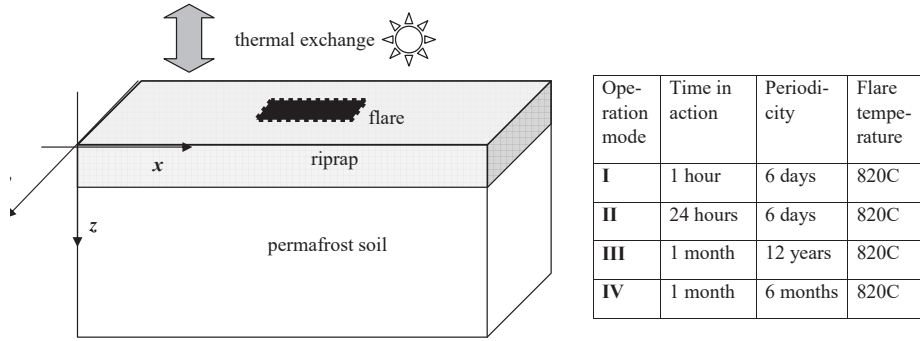
FIGURE 2. Simulated area with a flare platform (left). Types of operation modes of flare (right).

distribution in the soil is presented in fig. 1,left. In fig. 1,right monthly averages air temperature and solar radiation through a year used for simulation the annual temperature cycle in the soil are shown.

We consider a horizontal flare, which is simulated by a heat source on the surface of the permafrost soil (fig. 2,left). The flare platform (FP) is situated in the center of the domain surface, it has a rectangular form.

Simulation of processes of heat distribution is reduced to solution of three-dimensional diffusivity equation with non-uniform coefficients including localized heat of phase transition — an approach to solve the problem of Stefan type, without the explicit separation of the phase transition in the domain. The equation has the form

$$\rho\left(c_v(T) + k\delta(T - T^*)\right)\frac{\partial T}{\partial t} = \nabla\left(\lambda(T)\nabla T\right), \tag{1}$$

with initial condition

$$T(0, x, y, z) = T_0(x, y, z). \tag{2}$$

Here ρ is density $[kg/m^3]$, T^* is temperature of phase transition $[K]$,

$$c_v(T) = \begin{cases} c_1(x, y, z), & T < T^*, \\ c_2(x, y, z), & T > T^*, \end{cases} \text{ is specific heat [J/kg K]},$$

$$\lambda(T) = \begin{cases} \lambda_1(x, y, z), & T < T^*, \\ \lambda_2(x, y, z), & T > T^*, \end{cases} \text{ is thermal conductivity coefficient [W/m K]},$$

$k = k(x, y, z)$ is specific heat of phase transition, δ is Dirac delta function.

TABLE 1. Basic thermal parameters of riprap layers and soil

| | Layers of riprap and soil | Thermal conductivity, W/(m K) | | Volumetric heat, kJ/(m^3 K) | | Heat of phaze transition, kJ/(m^3 K) | Temperature of phaze transition, C |
		frozen	melted	frozen	melted		
1.	concrete slab 0-0.15 m.	1.93	1.57	2150.0	3490.0	141504.0	0.0
2.	breakstone 0.15-0.25 m.	1.75	1.63	2160.0	2630.0	83616.0	-0.8
3.	sand 0.25-2.35 m.	1.83	1.39	1536.0	1983.0	69505.8	-0.1
4.	soil 2.35-10.35 .	1.89	1.68	2200.0	2780.0	90983.7	-0.8
5.	soil 10.35-40.0 .	2.21	1.75	2350.0	2750.0	64461.7	-0.8

The computational domain is a three-dimensional box, where x and y axes are parallel to the ground surface and the z axis is directed downward (fig. 2,left). We assume that the size of the box is defined by positive numbers L_x, L_y, L_z: $-L_x \leq x \leq L_x$, $-L_y \leq y \leq L_y$, $-L_z \leq z \leq 0$.

The flare platform is simulated by a region of fixed temperature in a upper boundary (fig 2,right). Balance of heat fluxes at the surface $z = 0$ outside of the flare platform and on the platform outside of the operation period is defined by corresponding nonlinear boundary condition

$$\gamma q + b(T_{air} - T(x, y, 0, t)) = \varepsilon\sigma(T^4(x, y, 0, t) - T_{air}^4) + \lambda\frac{\partial T(x, y, 0, t)}{\partial z}. \tag{3}$$

To determine the parameters in boundary condition (3), an iterative algorithm is developed that takes into account the geographic coordinates of considered area, lithology of soil and other features of the selected location [2] .

The others parameters in condition (3) are determined as a result of geophysical research of oil and gas field. Fig. 1,left shows temperature distribution in an exploratory well. In Table 1 the soil structure and the thermal parameters are presented. Applying the developed iterative algorithm to define some of the parameters in nonlinear boundary condition (3) it is possible to identify them so that the temperature distribution in the soil found as a solution of equation (1)–(3) to be periodically repeated over the next few years, that allows to implicitly take into account different climate and natural features of the considered geographical location.
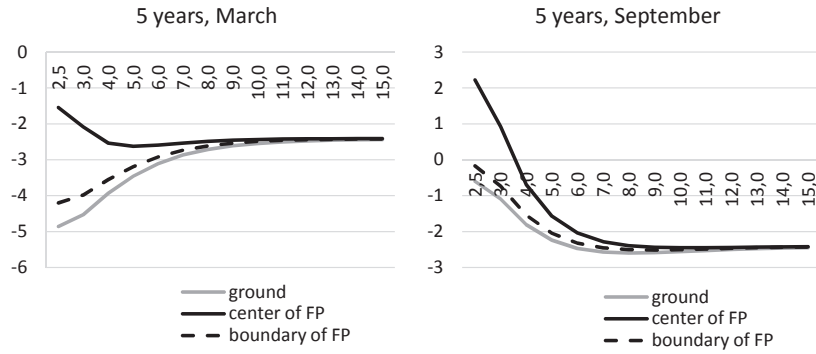
FIGURE 3. Vertical temperature profile after 5 years of I operation mode on March (left) and on September (right).
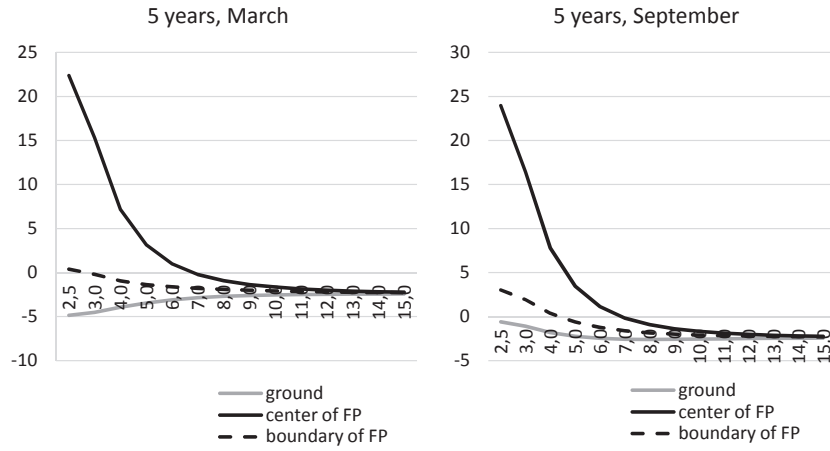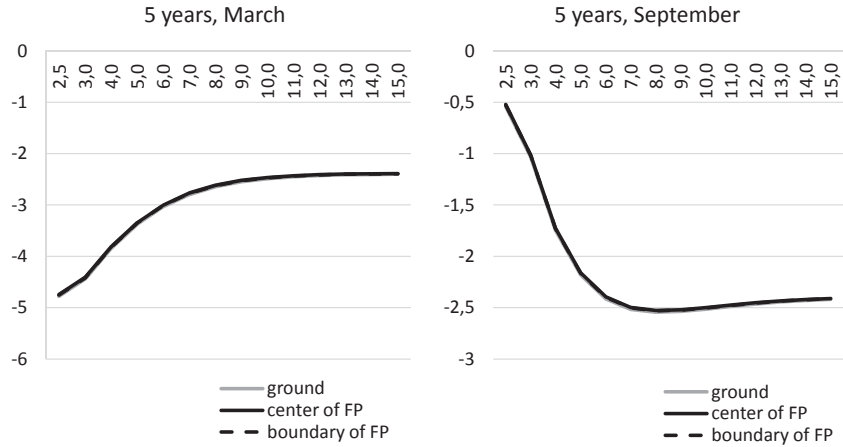
FIGURE 4. Vertical temperature profile after 5 years of II operation mode on March (left) and on September (right).

At the boundaries of the computational domain the boundary conditions are given

$$\left.\frac{\partial T}{\partial x}\right|_{x=\pm L_x} = \left.\frac{\partial T}{\partial y}\right|_{y=\pm L_y} = 0, \quad \left.\frac{\partial T}{\partial z}\right|_{z=-L_z} = 0. \tag{4}$$

The sizes of the domain L_x, L_y, L_z nave to be large enough to avoid an influence of the boundary conditions.
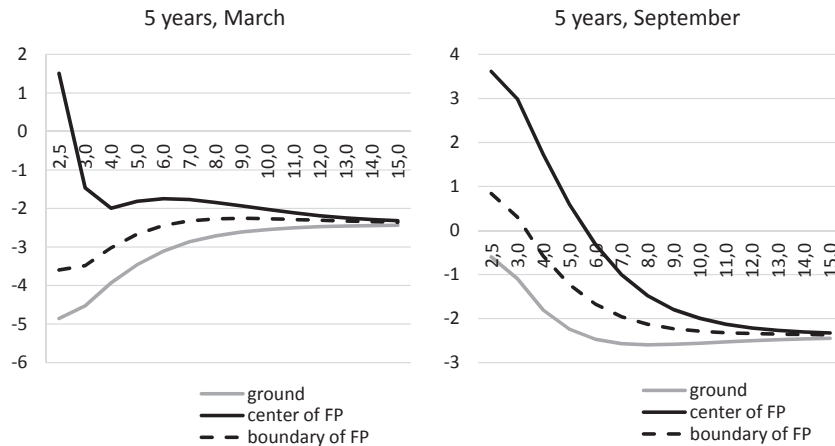

FIGURE 5. Vertical temperature profile after 5 years of III operation mode on March (left) and on September (right).

NUMERICAL RESULTS

The developed mathematical model allows to take into account the most significant physical and climatic factors influencing on formation of temperature fields in permafrost during operation of flare system. Implicit method of solution allows to use different scales of time steps in numerical simulation.

We consider 4 operation modes (fig. 2,right).

FIGURE 6. Vertical temperature profile after 5 years of IV operation mode on March (left) and on September (right).

I operation mode is a short-scale regime with 1 hour of burning the flare per each 6 days (144 hours). Temperature is supposed to be 820°C and 20°C in the center of the flare platform and on the boundary, respectively. Out of the operation period the flare heat dissipates and the natural thermal field is restored.

II operation mode is also a 6-days cycle, but the time of operation and heating is 24 hours (1 day) per each 6 days. The heating is more intense.

III operation mode is a long-scale regimen with 1 month of operation per 12 years (144 months). In spite of that the heating is extensive there is a long-time period for restoring.

IV operation mode is a combination of long-scale heating and short-time restoring with 1 month of operation per 6 months.

In Figure 3–6 the temperature profiles in *z* under 2,5 m (under the riprap and just in the soil) are presented on March (a coldest month) and on September (a warmest month) after 5 years of operation. The grey solid line corresponds to the ground temperature, the black solid and dashed lines correspond to the heat accumulated in the ground in the center of flare platform and on the boundary, respectively. For the Ist operation mode the temperature in the soil is relatively small and varies in accordance with the annual cycle. For the IInd operation mode the temperature is high independently of the season. For the IIIrd operation mode the temperature is close to the natural ground temperature. For the IVth the temperature varies with season, but the zone of thawing is larger.

Let consider the front of thawing under the flare platform during 7 years. In Figure 7 the deep of the soil thawing is presented. The deep is shown on September. The front of thawing stabilizes for 3rd year, after that the changes are insignificant. The maximal deep of thawing is reached by the IInd operation mode, but the temperature fluctuations durig annual changes corresponds to the IVth operation mode.

Effect of heating for I operating mode is not too intense, but is permanent, and its influence is presented even at the depth of 3m. Operating mode II is obviously has a significant effect on the temperature distribution under the flare platform, the deepest soil thawing is observed in this mode. When the flare heated for a month (operating mode III), despite the fact that high peak temperature is observed, but significant period of rest allows ground to be cooled up to near background values of temperature.

CONCLUSION

On the base of a mathematical model of thermal field in a nonuniform frozen soil from a heat source located on the surface of the ground, a horizontal flare system used to gas flaring in northern oil and gas fields is simulated. Forecasts of permafrost degradation around this system is obtained for different operating modes. The purpose of simulations is making recommendations on the optimal choice of the structure of heat-insulating riprap layers to reduce the thermal effects on the permafrost. The features of thermal field propagation in the soil are considered in detail, taking into
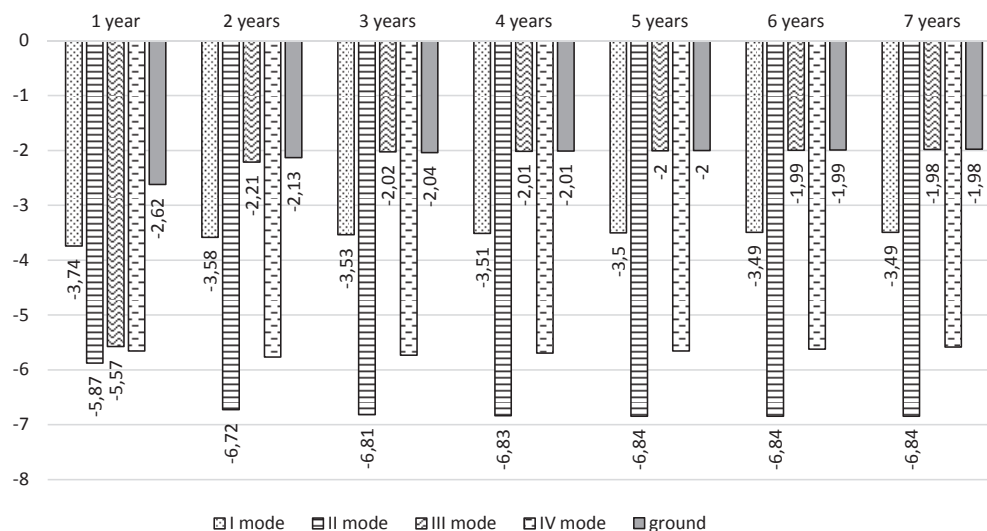
FIGURE 7. Level of thawing [deep in meters] under the flare platform different operation modes.

account different physical and climatic factors. Simulations allow to estimate deep of the soil thawing. Operating modes, when the flare platform time could be possible to cool down without heat accumulation, are preferable.

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