Long-term forecasting of changes in permafrost near wells and different technical systems

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Abstract

To simulate non-stationary temperature fields in permafrost from wells and other systems there have been developed a new three-dimensional mathematical model, which takes into account not only climatic factors such as seasonal changes in temperature and solar radiation due to the geographical location of the field, and physical factors (different thermal characteristics of uniform ground which change over time), but also shells and engineering constructions of wells and technical systems [1, 2]. Based on this model, a software complex Wellfrost is developed and certified. This software has been tested for seven oil and gas fields located in a permafrost zone, for which on the basis of numerical experiments a recommendations are formulated and the corresponding Regulations have been reviewed and approved in Rostekhnadzor. Comparison of numerical and experimental data for the field "Russkoe" has shown that the accuracy of the numerical results is approximately 5 % in determining the position of the thawing boundary from a well during three years of its operation. This fact allows to suggest that the developed algorithm and software package Wellfrost is approved and may be recommended for using in the oil and gas industry and construction, especially in "cloud technology" application, when organization of numerical computations on multi-processor computers is integrated with package of open NASA climate databases and with development of by appropriate interface.

1 Introduction

Permafrost takes place about 25 % of the total land area of the globe. In Alaska it occupies about 80 % of the total area, in Russia – about 65 %, in Canada – about 50 %. For example, in China these regions takes place 11 % of the territory, in Austria – 2 % (16000 km^2). Russia has reserves is about $19000km^3$ of underground ice in permafrost, this fact allows to call the permafrost as an underground glaciations. Ice-saturated rocks thawing due to global warming, or various technogenic influences, will be followed by the earth surface subsidence and development of cryogenic hazardous geological processes, called thermokarst. Permafrost degradation leads to considerable difficulties in various engineering structures constructing and operating, some of which are already in poor condition. This problem is compounded by possible global warming, which now obliges to ensure the reliability of the conservation status of frozen soil during constructing period. According to different estimates average air temperature increased by $0.2°C$ to $2°C$ or more during the past decade, and permafrost temperature increased by up to $1°C$. If this climate change persists, some climatologists predict air temperature increase from $1.0°C$ to $1.5°C$ by 2025 and from $2°C$ to $4°C$ by 2050. In this case, after 50 years in Russia with such a climate warming the boundary of permafrost in Western Siberia, will move to the North by 200—400 km. According to different Global Climate Models (GCM) [3] the average

annual temperature of the earth could rise by $2° - 6°C$ in 2099, which would increase the active layer thickness (ALT), the depth of the layer of freezing (thawing), by 0.5—2 m. All these facts would create a risk of permafrost degradation, and thus to reduce a bearing capacity of soil foundations when the temperature rises and permafrost loss of their stability during thawing. These reasons call to develop and use appropriate mathematical models and new technical solutions that can compensate the negative impacts of climate change for existing, for under construction and for planned facilities.

2 Mathematical model

First let consider heat exchange on a flat ground surface directly illuminated by the sun. Let the initial time be $t_0 = 0$, and the ground is a box Ω and has a temperature $T_0(x, y, z)$. 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. We assume that the size of the box Ω is defined by positive numbers L_x, L_y, L_z: $-L_x \leq x \leq L_x$, $-Ly \leq y \leq L_y$, $-L_z \leq z \leq 0$. Let $T = T(t, x, y, z)$ be soil temperature at the point (x, y, z) at the time moment t. The main heat flow associated with climatic factors on the surface $z = 0$ is shown in Figure 1.

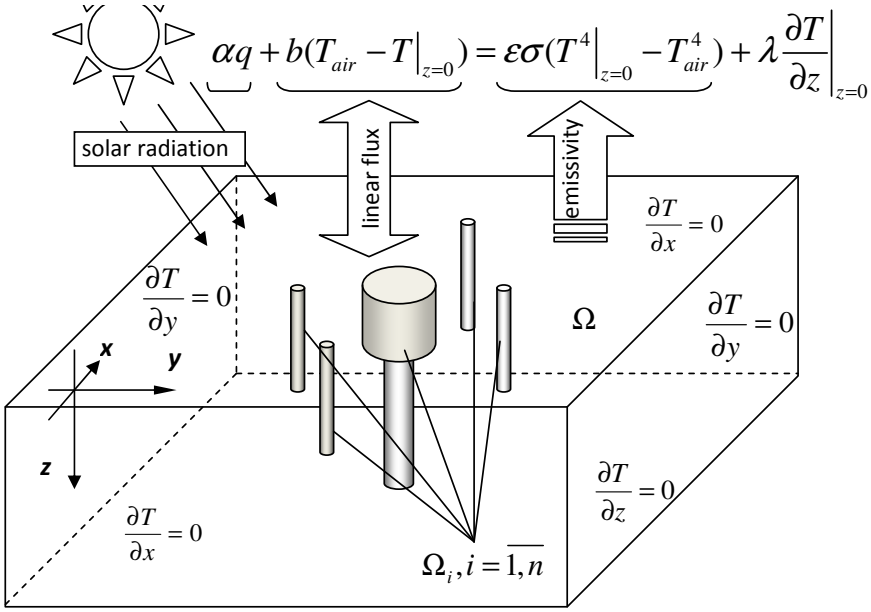


Figure 1: The main heat flows and boundary conditions.

$T_{air} = T_{air}(t)$ denotes the temperature in the surface layer of air, which varies from time to time in accordance with the annual cycle of temperature; $\sigma = 5,67 \cdot 10^{-8}\ Wt/(m^2K^4)$ is Stefan-Boltzmann constant; $b = b(t, x, y)$ is heat transfer coefficient; $\varepsilon = \varepsilon(t, x, y)$ is the coefficient of emissivity. The coefficients of heat transfer and emissivity depend on the type and condition of the soil surface. Total solar radiation $q(t)$ is the sum of direct solar radiation and diffuse radiation. Ω can include a number of engineering structures. Suppose that in Ω there are n objects that are heat sources (for example producing insulated wells, pipelines). We denote the surface of these objects by $\Omega_i = \Omega_i(x, y, z)$, $i = 1, ..., n$ (Fig.1).

Thus, the modeling of thawing in the soil is reduced to the solution in Ω of the equation

following heat equation [1, 2]:

$$\rho\big(c_\nu(T) + k\delta(T - T^*)\big)\frac{\partial T}{\partial t} = \mathrm{div}\,(\lambda(T)\mathrm{grad}T), \tag{1}$$

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

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

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

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

Thus, it is necessary to solve equation (1) in the area Ω with initial condition

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

and boundary conditions

$$\alpha q + b(T_{air} - T_{z=0}) = \varepsilon\sigma(T^4_{z=0} - T^4_{air}) + \lambda\frac{\partial T}{\partial z}, \tag{3}$$

$$T\Big|_{\Omega_i} = T_i(t), i = 1, \ldots, n, \tag{4}$$

$$\frac{\partial T}{\partial x}\Big|_{x=\pm L_x} = \frac{\partial T}{\partial y}\Big|_{y=\pm L_y} = \frac{\partial T}{\partial z}\Big|_{z=\pm L_z} = 0. \tag{5}$$

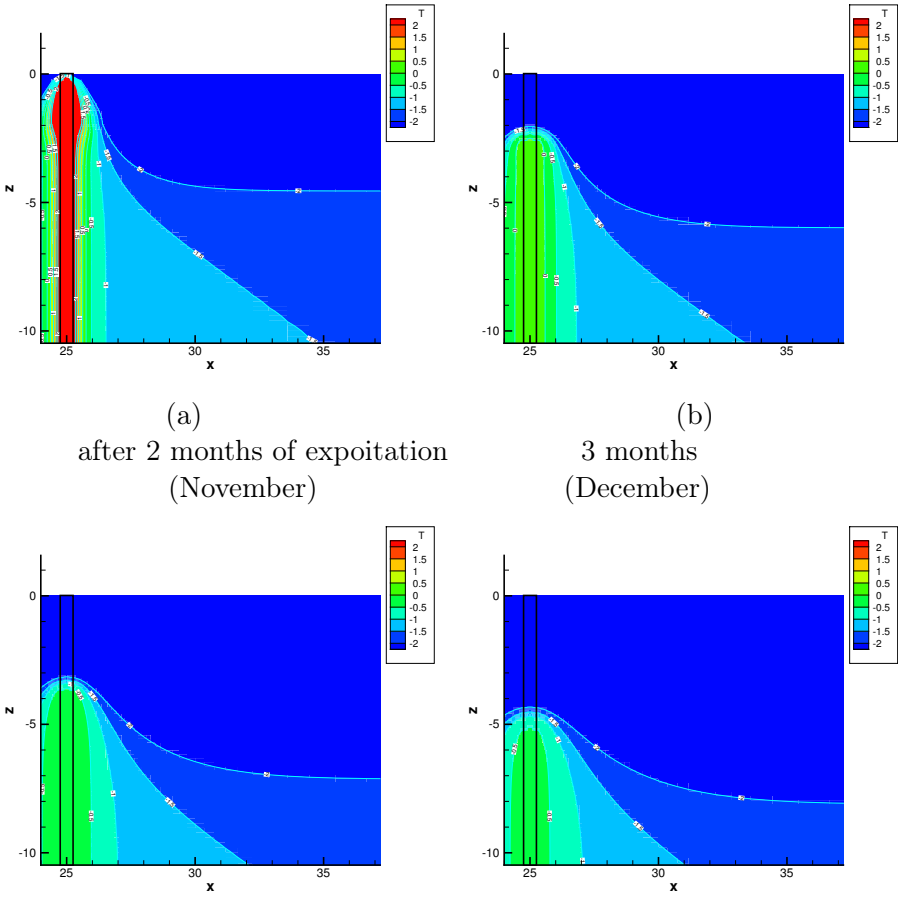
Thus, the simulation of heat transfer in three-dimensional domain with the phase transition is reduced to solving the initial-boundary value problem (1)–(5).

The base of this numerical method is an algorithm with good reliability in finding thermal fields of underground pipelines [4, 5], but in view of specificity, related to the possible phase transitions in the soil [1, 2].

3 Numerical results

Let consider computational results for two different engineering facilities affecting the thawing of permafrost. The first object is a single production well with a special mode of operation, the second one is the system used for gas flaring at oil production.

In Fig. 2 the thermal fields in the soil are shown up to the depth of 10 meters for the well, which operated two months (October and November) and then the well operation is stopped and the cooling of the soil is shown for three next months.



(a)
after 2 months of expoitation
(November)

(b)
3 months
(December)

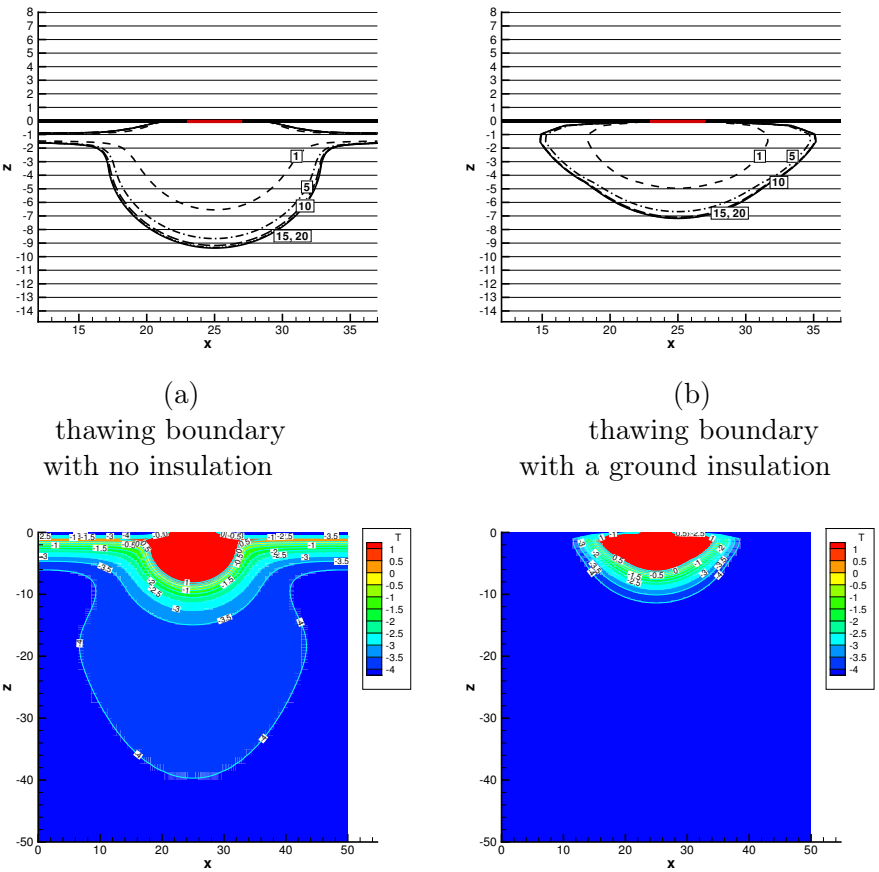
(c)
4 months (January)

(d)
5 months (February)

Figure 2: Cooling of production well.

In Fig. 3 the thermal fields are shown, which arise when modeling flare (the temperature of the burning of associated gas is assumed to be $800°C$) installed on the ground without insulation (Fig. 3a and 3c) and with a thermal insulation on the ground (Fig. 3b and 3d). Calculations allow us to evaluate the effectiveness of soil insulation and to determine the boundary of melted soil. Calculations showed that the stabilization of the melting boundary is reached after 15 years of flare system operation in both cases.

Therefore, these results enable us to make long-term forecasts for the thawing of the permafrost around the various engineering systems according to different climatic and physical factors.



(a) thawing boundary with no insulation

(b) thawing boundary with a ground insulation

thermal field for 5 years with no insulation

thermal field for 5 years with a ground insulation

Figure 3: Thermal fields under a flare system.

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