Supercomputer Technologies for Long-term Modeling of Permafrost Changes

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Abstract. A model of propagation of thermal fields in permafrost from various engineering objects operating in Arctic regions is considered. The proposed model includes the most significant technical and climatic parameters affecting the formation of thermal fields in the surface layer of the soil. The main objective of the study is a long-term forecasting of changes in the dynamics of permafrost boundaries during operation of cluster sites of northern oil and gas fields. Such a forecast is obtained by simulation of complex system consisting of heat or cold sources and frozen soil, thawing of which can lead to the loss of the bearing capacity and possible technogenic and environmental accidents. For example, the sources of heat can be production wells, and the sources of cold can be seasonal cooling devices that are used to stabilize the soil. To minimize the impact of heat sources on permafrost, various options for thermal insulation are used, and to preserve the original temperature regime of the top layer of soil, riprap materials consisting of sand, concrete, foam concrete, or other heat insulating material are used. The developed set of programs was used in the design of 12 northern oil and gas fields. To solve the described problem in a complex three-dimensional area, substantial computational resources are required. The computing time of one variant can often exceed 10–20 hours of machine time on a supercomputer. To speed up the numerical calculations, multicore processors are used. Numerical calculations illustrate the possibility of a developed set of programs for making long-term forecasts for determining changes in the boundaries of the permafrost zones, and show that on multicore processors it is possible to achieve acceleration close to the theoretical one.

Keywords: Heat and Mass Transfer, Cryolithozone, Simulation, Parallel Computing, OpenMP.

1 Introduction

The term “*permafrost*” was introduced into the English literature by S.W. Muller [1] as an abbreviation of the original Russian term “*Permanently frozen ground (soil)*” suggested by M.I. Sumgin [2]. The permafrost zone occupies about 25% of all the land of the globe [3], [4] and is located in the northern or mountainous regions under the zone of seasonal thawing of the soil, which is determined by geographical coordinates, the intensity of solar radiation, and other climatic factors. The climate changes related with, for example, the warming may lead to the essential permafrost degradation especially in high-latitudes regions, which may influence on the environment of the globe [4], in particular, due to the release of methane.

The development of the permafrost regions is especially important for Russia, since about 93% of Russian natural gas and 80% of oil are produced in these areas. At the same time, the development of these regions leads to negative consequences associated with the thawing of permafrost, which leads to the formation of dangerous geological phenomena called thermokarst. The average thickness of the permafrost varies from 10 to 800 meters, and the components of the permafrost soils have various physicochemical properties that can vary in all directions. In summer, as a result of positive temperatures and solar radiation, seasonal thawing of the upper soil layer occurs; in winter, the reverse process is observed. Computer simulation of such seasonal processes is described in [5], and, in particular, with using multicore processors and OpenMP technology in [6]. A significant effect on the formation of thermal fields in the soil is also caused by anthropogenic conditions, often leading to more extensive changes in the boundaries of the permafrost [7], [8]. In well pads of northern oil and gas fields the following technical systems may have the same effect of a massive heat source: production and injection wells [9], [10], flare systems [11] having some periodical operation conditions [12] and other engineering facilities. For thermal stabilization of the soil (including additional cooling or refreezing), the cooling devices (SCDs) are used that can reduce thermal effects from heat sources on the surrounding soil and can be used to prepare a construction site in the permafrost distribution zone by freezing the upper part of the soil [13].

To solve the described problems, mathematical models, numerical methods of solution, and codes are developed for modeling non-stationary thermal fields in the near-surface soil layer in a complex three-dimensional area. The computational time of the problems solution, for which a large number of variants with different parameters are required, could exceed tens of hours of computer time on a supercomputer. The parallel approaches are considered [14], and cloud technologies were also used, which allow to carry out remote computing to solve certain problems arising from the placement and operation of northern oil and gas fields [15], [16]. In this work, we studied the use of multicore processors and OpenMP technology to solve the problems of long-term forecasting of changes in the thawing boundaries of permafrost around a production well. The results of numerical calculations and evaluation of the effectiveness of multicore processors are presented.

2 Problem Statement and Mathematical Model

Let $T = T(t, x, y, z)$ be the soil temperature at the time moment t, where (x, y, z) is a point of the computational area $\Omega = \{(x, y, z): 0 \leq x \leq L_x, 0 \leq y \leq L_y, -L_z \leq z \leq 0\}$. The area is a 3D “box” (see Fig. 1), in which the cylinder-shaped well Ω_1 and the cold sources (SDCs) Ω_2 are excluded. The axes x and y are parallel to the soil surface, and the axe z is directed vertically down into Ω. In Fig. 1 there presented two variants of the unit combinations: a single well and a well surrounded by SCDs.

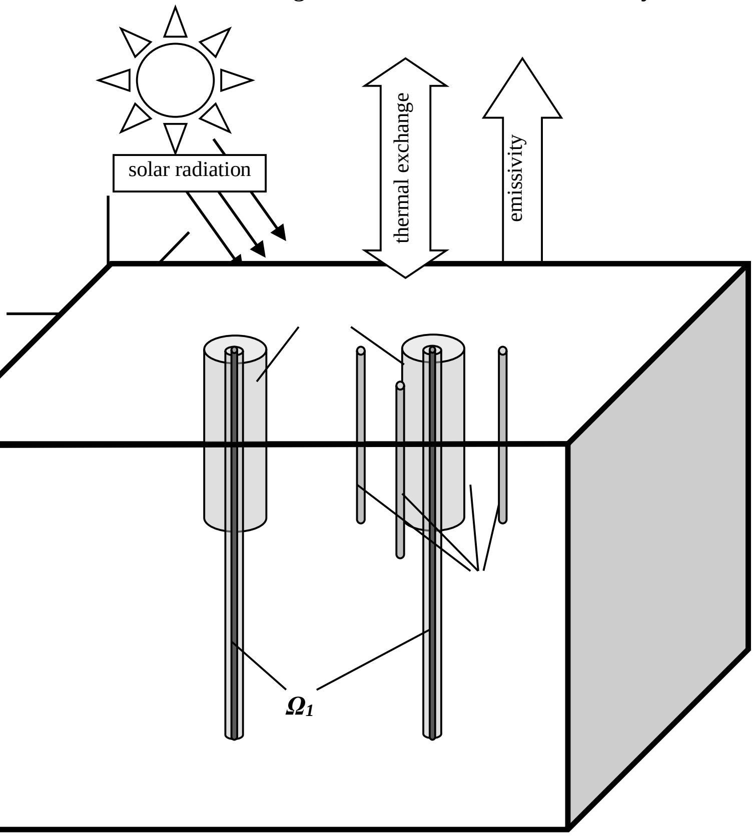


Fig. 1. The domain Ω, well Ω_1, and seasonal cooling devices Ω_2.

Thermal conductivity processes are described by the following equation:

$$\rho\left(c_v(T) + k\delta(T - T^*)\right)\frac{\partial T}{\partial t} = \mathrm{div}\left(\lambda(T)\ \mathrm{grad}\ T\right) \qquad (1)$$

with the initial condition

$$T(0, x, y, z) = T_0(x, y, z), \qquad (2)$$

where $\rho=\rho(x,y,z)$ is density [kg/m^3], $T^*=T^*(x,y,z)$ is temperature of phase transition,

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

$\lambda(T)= \begin{cases} \lambda_1(x,y,z), \text{ for } T<T^* \\ \lambda_2(x,y,z), \text{ for } T>T^* \end{cases}$ is thermal conductivity [W/(m K)], δ is Dirac δ-function, $k=k(x,y,z)$ is specific heat of phase transition. The justification of the applicability of this equation for solving problems of the Stefan type is presented in [17], [18]. In [19] as a result of the heat balance on the surface, the following boundary condition is proposed:

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

and an algorithm for adaption of the mathematical model to a specific geographic location is described. In condition (3) $T_{air}(t)$ denotes the temperature in the surface layer of air, which varies from time to time in accordance with the annual cycle of temperature, σ = 5,67·10-8W/(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. Soil is absorbed only a part of the total radiation which equal to $\alpha q(t)$, where $\alpha=\alpha(t,x,y)$ is the part of energy that is formed to heat the soil, which in general depends on atmospheric conditions, angle of incidence of solar radiation, i.e. latitude and time. The technical objects Ω_1 and Ω_2 are additional sources of heat or cold in the permafrost soil. At these inner boundaries we set the following conditions:

$$T|_{\Omega_i} = T_i(t), \quad i = 1,2. \tag{4}$$

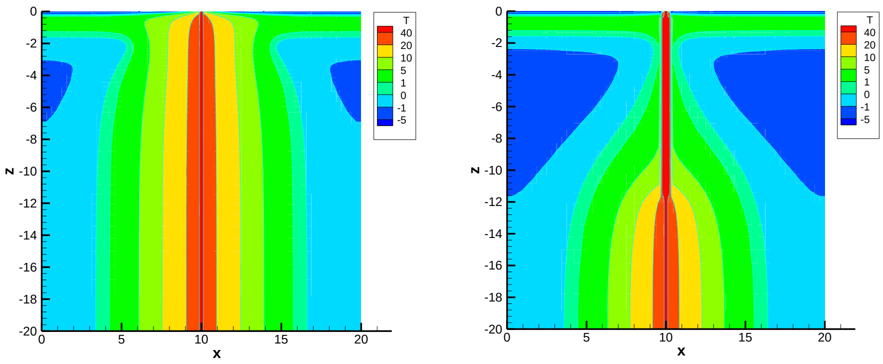
To use the numerical methods it is necessary to set the boundary conditions at the lateral boundaries of Ω. Let suppose

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

In this case, the computational domain should be chosen large enough to avoid the influence of the boundary conditions (5) on the thermal fields in the computational domain Ω created by the objects Ω_i.

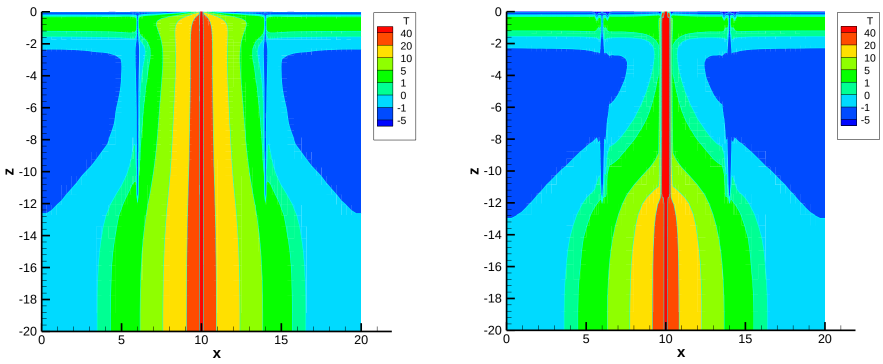
3 Numerical Calculations and Performance Study

To apply a numerical method of solution of the problem (1)–(5) it is necessary to evaluate the parameters included into boundary condition (3). In [19], [20] an iterative algorithm is described to determine these parameters. The choice of these parameters allows to indirectly take into account the influence of snow cover, climatic, and environmental conditions associated with the geographical coordinates of the considered well pad. In the numerical implementation of the solution of problem (1)–(5), the finite-difference method is used, which allows to apply the method of splitting into spatial variables for better organization of numerical calculations. Following [17] and [18] equation (1), for each of the spatial directions, the equation is approximated by an implicit central-difference three-point scheme, and the system of difference linear algebraic equations having the tri-diagonal form is solved by the sweep method. On the ground surface, in view of condition (3), a fourth-degree algebraic equation arises, for the solution of which the Newton method is used [21]. In the computations, an orthogonal grid is used, which is uniform or condensing near the soil surface, or the surfaces Ω_i.



(a) (b)

Fig. 2. The thermal fields after 5 years of operation for the non-insulated well (a) and for the well with a complex shell (b).



(a) (b)

Fig. 3. The thermal fields after 5 years of operation for the non-insulated well (a) and for the well with a complex shell and a system of SCDs (b).

The described algorithm is implemented in the “Wellfrost” certified software package and in the various modifications, which was tested at 12 northern oil and gas fields. Also the experimental data and the results of numerical calculations was compared in view to determining the boundary of the location of the zero isotherm, which determines the boundary of the area of soil thawing around the producing well. In 2012 the accuracy of numerical calculations was verified for the Russkoye oil field (Yamalo-Nenets Autonomous Okrug, Russia), for which the obtained numerical results are in accordance with the experimental results, and the accuracy reached 5% after 3 years from the start of the field operation.

In Figures 2 and 3 the calculated thermal fields are shown for 5 years of operation around the well without heat-insulating shells (a) and with a combined heat-insulating shell (b), as well as with a system of 8 SCDs.

The permafrost soil temperature is -0.7°C, the temperature of the fluid in the well is 50°C. Calculations allow to evaluate the influence of heat or cold sources, the zone of seasonal thawing and freezing of the upper soil layer. To assess the long-term impact, calculations are carried out for a time period of up to 50 years, the time step does not exceed 24 hours. The calculation time depends both on the size of the computational grid and on the complexity of the objects introduced into the computational domain.

Table 1 shows the considered variants of the calculations. Fig. 4 shows a graph of the change of calculation time for each of the model variants. The calculations were carried out on a grid with 91x91x51 nodes.

Table 1. Descriptions of the model variants.

No.	Description
1	Freezing and thawing of soil without inserted objects.
2	Thawing of the soil around the well without thermal insulation.
3	Thawing of the soil around the well with a simple insulation.
4	Thawing of the soil around the well with a complex insulation.
5	Freezing of the soil with 9 SCDs.
6	Freezing and thawing of the soil around the well without thermal insulation and 8 SCDs.
7	Freezing and thawing of the soil around the well with a simple insulation and 8 SCDs.
8	Freezing and thawing of the soil around the well with a complex insulation and 8 SCDs.

The computing time increases nonlinearly when the number of the included object grows, as well as, the complexity of the objects, even if the grid size remains the same.

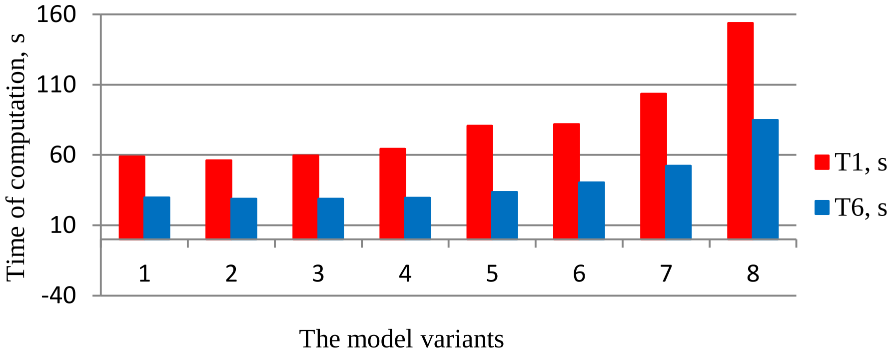


Fig. 4. Computational times of 1 year for different variants: sequential program execution time (red), execution time on 6 cores (blue).

Table 2 contains the computing times of the parallel program for simulating 1 year on the 6-core AMD Ryzen 5 1600X processor. T_1 is the computing time of the serial program, T_6 is the computing time of the parallel program running on 6 cores.

Table 2. Computing time of the serial and parallel programs for various models.

No.	T_1 [s]	T_2 [s]	Speedup S_6	Efficiency E_6
1	59	29.7	1.98	0.33
2	56.2	28.8	1.95	0.32
3	59.6	29.5	2.01	0.34
4	64.3	33.6	1.91	0.32
5	80.8	38.1	2.12	0.35
6	81.8	40.5	2.01	0.34
7	103.7	52.4	1.98	0.33
8	153.8	84.9	1.81	0.30

For studying the parallel algorithm running on n cores, the speedup $S_n = T_1 / T_n$ and efficiency $E_n = S_n / n$ coefficients were used. The resulted values are consistent with the theoretical ones, obtained by the Amdahl's law $\overline{S_n} = \dfrac{1}{\alpha + \dfrac{(1-\alpha)}{n}} = 2.2$, where $\alpha = 0.35$ is the serial code proportion.

4 Conclusion

The developed models and algorithms make it possible to simulate the propagation of unsteady thermal fields in frozen ground from producing wells at well pads, taking into account the possible placement of cooling devices around the wells. The numerical experiments show the possibility of obtaining a long-term forecast in the dynamics of permafrost boundaries for various options for well operation using additional technical systems and heat-insulating materials. The complications and additional constructions inserted into the model by taking into account various additional sources of cold, for example the SCDs, and the use of thermal insulation increase the computational time. Parallel computations approaches significantly reduced the computational time in solving such problems. A parallel software package for multicore processors using OpenMP technology has been developed.

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