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RESEARCH ARTICLE

Modeling of thermophysical processes in an oil reservoir during heating in a stopped well

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Abstract

Objectives. An important and urgent task of the oil producing industry is the identification of patterns of thermophysical processes in reservoirs. One approach to improving the efficiency of oil recovery in conditions of hard-to-recover reserves involves thermal action on the reservoir. The construction of mathematical models for describing such processes to optimize production technologies is based on the formation of nonstationary heat flows in the reservoir when a stopped well is heated. The application of mathematical modeling methods considered in the work forms a basis for calculating the distribution dependencies of nonstationary fields of thermophysical characteristics in the reservoir when heating the well to its parameters and the properties of the environments.

Methods. The work is based on heat- and mass-transfer theory along with mathematical physics, analytical and numerical methods, as well as algorithms, computer modeling approaches, and the development of applications using modern programming languages and their libraries.

Results. A formation saturated with oil, water, and a steam–gas mixture is theoretically described. A closed system of heat and mass transfer equations is obtained taking into account diffusion-droplet and heat flows and phase transformations. A formulated mathematical statement of the model comprises an initial–boundary value problem for equations relating the temperature, saturation, and pressure of the components of the saturating fluid in the formation. Numerical algorithms for solving are developed and their software implementation carried out. An application developed for computer implementation of the model provides convenient visualization of the calculation results consisting of several components (modules). Numerical experiments were carried out using the developed software to study how various factors, such as the properties of the formation sketch and the saturating liquid phase and heater characteristics, affect the thermophysical processes in the formation.

Conclusions. The developed model can be used to clearly describe nonstationary distributions of thermophysical characteristics formed by thermal and diffusion-droplet flows in the reservoir during heating of a shut-up well. The obtained results expand current understandings of the regularities of thermophysical processes and the properties of the saturating phase in the reservoir under thermal influence.

Keywords: thermophysical processes, heat transfer, mass transfer, heat flow, diffusion-droplet flow, heat equation, heat transfer equation, thermal conductivity, thermal impact on the formation, oil well heating

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НАУЧНАЯ СТАТЬЯ

Моделирование теплофизических процессов в нефтяном пласте при прогреве в остановленной скважине

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Резюме

Цели. Выявление закономерностей теплофизических процессов в пластах является важной и актуальной задачей нефтедобывающей отрасли. Одним из способов повышения эффективности нефтеотдачи в условиях трудноизвлекаемых запасов является тепловое воздействие на пласт. При нагреве остановленной скважины в пласте формируются нестационарные тепловые потоки, поэтому в вопросах оптимизации добывающих технологий таких процессов широко применяется построение адекватных математических моделей. Цель работы – развитие возможностей применения методов математического моделирования и установление на их основе зависимостей распределения нестационарных полей теплофизических характеристик в пласте при нагревании скважины от ее параметров и свойств сред.

Методы. Использованы теория тепло- и массопереноса, методы математической физики, аналитические и численные методы, алгоритмы, методы компьютерного моделирования и разработки приложений, современные языки программирования и их библиотеки.

Результаты. Проведено теоретическое описание пласта, насыщенного нефтью, водой и парогазовой смесью. Получена замкнутая система уравнений тепло- и массопереноса при учете диффузионно-капельных и тепловых потоков и фазовых превращений. Сформулирована математическая постановка модели, представляющая собой начально-краевую задачу для уравнений, связывающих температуру, насыщенность и давление компонентов насыщающей жидкости в пласте. Разработаны численные алгоритмы решения такой задачи и проведена их программная реализация. Разработано приложение для компьютерной реализации модели с удобной визуализацией результатов расчетов, состоящей из нескольких компонентов (модулей). С использованием разработанного программного обеспечения проведены численные эксперименты для изучения того, как различные факторы, такие как свойства скетча пласта и насыщающей жидкой фазы, характеристики нагревателя, влияют на теплофизические процессы в пласте.

Выводы. Разработанная модель позволяет наглядно описать нестационарные распределения теплофизических характеристик, формируемых тепловым и диффузионно-капельным потоками в пласте в процессе прогрева остановленной скважины. Полученные результаты расширяют представления о закономерностях теплофизических процессов и свойствах насыщающей фазы в пласте при тепловом воздействии.

Ключевые слова: теплофизические процессы, теплоперенос, массоперенос, тепловой поток, диффузионно-капельный поток, уравнение теплопроводности, уравнение теплопереноса, теплопроводность, тепловое воздействие на пласт, прогрев скважины

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INTRODUCTION

The development of mathematical models of thermophysical processes in the reservoir as a means of increasing the efficiency of oil recovery, especially in conditions of hard-to-recover reserves, remains one of the urgent tasks in the oil producing industry [1]. Since thermal stimulation of the reservoir is one of the most efficient means to increase oil recovery under such conditions [2–4], the use of mathematical models to obtain various kinds of information on the heat transfer patterns in the reservoir is an important area of research [5, 6]. Nonstationary heat flows in the reservoir are formed during heating of a shut-in well. When the thermal stimulation ends, the reservoir begins to cool. The need to describe such processes is associated with economic imperative of maximizing oil production [7, 8]. To develop effective strategies, it is necessary to understand the dynamics of changes in temperature, saturation, and pressure in the reservoir [9]. Mathematical modeling is the main tool used in such research due to the need to consider the complex interaction of physical processes [10, 11]. The formulation of mathematical models of thermophysical processes is based on a system of heat transfer equations used in many thermophysical problems and heat conduction theory [12, 13].

Mathematical modeling of thermophysical processes in oil-producing wells and formations is described in many works [14–16]. Such studies have been actively continued in recent years using numerical methods and computer modeling [17, 18]. In particular, Tupysev [19] studied the regularities of non-isothermal gas filtration in a well during the creation of low-temperature gas deposits when the thermobaric conditions of the formation approach the equilibrium conditions of hydrate formation. The described method can be used to predict the exploration and operation of wells during the development of low-temperature gas deposits, as well as to determine the dynamics of possible hydrate formation in the bottomhole zone and the influence of this process on the operation of wells.

Sharafutdinov et al. [20] carried out a numerical study of the temperature field in a multi-layer well during the movement of gasified oil taking the Joule–Thomson effects and heat of degassing into account. The possibility of estimating the position of the boundary of the oil degassing region in the wellbore using the calculated temperature distribution was demonstrated.

Ramazanov and Parshin [21] proposed and analytically investigated a model describing the formation of a temperature field in the reservoir with a combined inflow of formation water and gassed oil to the well. The time of observation of the maximum temperature decrease was shown to be determined by the radius of the degassing zone and the speed of convective heat transfer (which depend on the specific flow rates of oil and water), and this time can be used to estimate such parameters. It was confirmed that, with an increase in water saturation, the influence of the cooling effect of oil degassing regularly decreases.

Ramazanov and Parshin [22] also determined the conditions for observing a non-monotonic change in temperature over time when the temperature at the outlet of a gas–liquid mixture from a porous medium initially decreases for some time and then increases.

Shagapov and Tazetdinov [23] propose a mathematical model describing the formation of a temperature field in a radially symmetric heated formation with high-viscosity oil through a horizontal well. The authors demonstrated the possibility of further exploitation of the well for the production of oil with reduced viscosity. A mathematical statement based on a system of equations is used to describe the heat transfer process for assessing the characteristic ranges of penetration of filtration and temperature waves for the time periods under consideration.

Ramazanov et al. [24] presented an algorithm and software package for calculating and modeling the process of oil displacement during hot water injection to obtain temperature fields in the formation at different points in time, as well as to determine the oil recovery of the formation taking into account the influence of the thermal characteristics of liquid-saturated rocks.

Gil'manov et al. [25] propose a mathematical model of cyclic–steam treatment of a formation taking into account the mass fraction of steam in the coolant and the equation of state for water. The model is based on the use of heat balance relations at each stage of cyclic steam treatment. The described model is used to determine the steam temperature in the productive interval along with the initial formation temperature. Here, the heat flow calculations are based on the data of short-term dynamic temperature studies, while the oil consumption was determined using the Dupuit formula for a zonally heterogeneous formation. The model was also used to determine the optimal times of the stages of cyclic–steam treatment and the maximum cumulative oil production. The optimal time for pumping the coolant into the formation and the well holding time for steam condensation were shown to increase with an increase in the thickness of the formation, the coolant consumption, and the mass fraction of steam in it.

The importance of the ongoing studies of thermophysical processes in formations and wells is due to the need to understand their patterns for developing technologies based on the thermal impact on the formation aimed at increasing the efficiency of oil extraction. Numerical methods and computer modeling are widely used to describe nonstationary distributions of the temperature field and pressure in formations and wells. However, despite the significant development of this problem already undertaken, a number of issues require more detailed study by methods of mathematical modeling.

The present work presents the results of the development and computer implementation of a model that describes the nonstationary process of heat flow distribution in a reservoir under constant thermal impact in a shut-in well (in which production is temporarily stopped). Based on the developed computer implementation of the model, the patterns and mechanisms of the influence of the thermophysical parameters of the reservoir on the nonstationary distribution of temperature, saturation, and pressure parameters in it are studied.

1. THEORETICAL BASIS OF THE MODEL

In the volume element of a formation saturated with oil, water, and a steam-gas mixture in thermodynamic equilibrium, the temperature T, pressure p, and saturation θ are distributed uniformly at the initial moment of time. If we neglect the compressibility of the formation skeleton and gravitational effects, then the continuity equation for each component of the saturating liquid phase can be written in the form [16, 26–30]:

$$m\frac{\partial(\rho\theta)}{\partial t} = -\mathrm{div}J_\theta + I, \tag{1}$$

where m is the porosity of the average, ρ is the component density; t is time, θ is the volumetric saturation of the mixture component of the element of the formation volume.

$$\theta = \frac{V}{mV_\mathrm{e}},$$

where V is the volume of the saturating liquid phase component in the formation volume element; V_e is the volume of the formation element; J_θ is the diffusion-droplet component of the mass density of the flow transferred by the molecular thermal conductivity of the formation volume element; and I is the volumetric power of the source of the liquid component.

In accordance with Fick's law, the diffusion-droplet component of the mass flux density can be represented as

$$J_\theta = -a(\nabla\theta + \delta\nabla T), \tag{2}$$

where a is the coefficient of diffusion-droplet mass transfer of the component of the saturating liquid phase, δ is its thermogradient coefficient, and ∇ is the nabla symbol ($\nabla\theta$ is the saturation gradient and ∇T is the temperature gradient).

The power of the source can be represented as

$$I = \varepsilon\rho m\frac{\partial\theta}{\partial t}, \tag{3}$$

where ε is the phase transition coefficient, representing the ratio of the increment in saturation of a liquid component obtained during a phase transition to the total increment in saturation of the liquid component taking into account diffusion, droplet, and convective processes.

The heat and mass transfer equation, taking into account Eq. (3), can be written in the form [16, 26–30]

$$c\frac{\partial T}{\partial t} = -\mathrm{div}J + \varepsilon q\rho m\frac{\partial\theta}{\partial t}, \tag{4}$$

where c is the specific heat capacity of the volume element of the formation; J is the heat flux density; q is the specific heat of phase transition.

According to Fourier's law, the heat flux density can be represented as

$$J = -\lambda\nabla T, \tag{5}$$

where λ is the effective thermal conductivity of an element of the formation volume.

To the given equations, the equation of state of the mixture should be added [16, 26–29]:

$$\rho\theta = \frac{pM}{zRT}(1+\theta), \tag{6}$$

where M is the molar mass of the mixture; R is the universal gas constant; z is the correction factor that takes into account the deviation of the vapor–gas mixture from an ideal gas.

Accurate to terms of the first order of smallness [16],

$$\nabla(\rho\theta) \approx \rho_e \beta \frac{\partial p}{\partial t},$$

where β is the coefficient of elasticity of the vapor–gas mixture; ρ_e is the density of the formation skeleton. The continuity equation that closes the system of equations for temperature and saturation can be written in the form:

$$\beta \frac{\partial p}{\partial t} = -\varepsilon \frac{\rho}{\rho_e} \frac{\partial \theta}{\partial t}. \quad (7)$$

The system of Eqs. (1)–(7) forms the theoretical basis for modeling thermophysical processes in the reservoir.

It should be noted that the values of the above-introduced coefficient of diffusion-droplet mass transfer, thermogradient coefficient, and phase transition coefficient are determined from experiments. In the general case, these coefficients may depend on both temperature and saturation. However, in experimentally established ranges of temperatures and saturations for a number of water-saturated specific media (sands, sandstones, clays, ceramics), the indicated coefficients are found to be practically constant.

For example, in the temperature range of 293–423 K, the phase transition coefficient ε is constant [16]. With increasing saturation in the range of 0.3–0.4, its value decreases linearly from 1.0 to 0.3, but with a further increase in saturation, it remains constant. The thermogradient coefficients δ behave completely similarly to the phase transition coefficient depending on temperature and saturation; in particular, its stabilized value in a number of media is $(0.2–0.5) \cdot 10^{-3}$ K^{-1}.

Although the coefficient of diffusion-droplet mass transfer *a* in the temperature range under consideration increases by approximately 1.5 times in some media (sands, sandstones), in a number of others (ceramics, clays), it is temperature-independent. Its stabilized values in sandy media are $(1.8–8.8) \cdot 10^{-4}$ kg/(m·s), while in ceramics and clays, the corresponding figure is $(4.4–8.9) \cdot 10^{-6}$ kg/(m·s).

The assumption of the constancy of these coefficients in theoretical modeling is valid in the case of low-intensity processes in which the temperature and saturations change insignificantly over short periods of time. For the purposes of constructing a model, an approach is also possible in which the heat and mass transfer processes under study are divided into separate sections in each of which the coefficients under consideration are considered constant.

2. FORMULATION OF THE MODEL AND STATEMENT OF THE PROBLEM

In this paper, we consider the stationary thermal effect of a borehole heater on a reservoir. We consider the reservoir as a continuous, homogeneous, thermally isotropic medium having constant effective values of thermophysical coefficients for calculating heat propagation in the reservoir during heating of a shut-down well. If the reservoir heterogeneity, evaporation processes, and diffusion-capillary mass transfer of the saturating medium are not taken into account when describing thermophysical processes, significant discrepancies may be found between the observed data taken from the wells and the calculated values. Noticeable discrepancies were noted between the calculated temperatures at the well bottom and the values recorded at the fields. The observed differences in the well flow rate and the formation cooling period after treatment between the calculated and actual values generally turn out to be greater than the calculated ones. Consequently, the influence of phase transitions and diffusion-capillary effects on heat propagation throughout the heated reservoir is significant in a number of cases.

A model of a homogeneous thermally isotropic reservoir with infinite thickness and extension is proposed to which access is provided through a borehole of zero diameter. We assume that a heater with zero diameter and finite length *h* is placed in the borehole. Let a single-component liquid in thermodynamic equilibrium with the vapor contained in it and a gas insoluble in the liquid be used to fill the reservoir to saturation. The borehole is considered to be stopped when its initial temperature (T_0), pressure (p_0), and liquid saturation (θ_0) are uniformly distributed.

On the wall of the heater at the initial moment of time $t = 0$, the specific heat flow *N* is abruptly formed and its value maintained at constant. Due to the formation of such a stationary flow, the temperature *T* increases and the liquid begins to evaporate. The increase in temperature and intensification of evaporation in turn lead to an increase in the partial and total pressure *p* and a decrease in the saturation of the liquid phase θ.

When formulating the model, the following assumptions are also taken into account. The reservoir has a high degree of saturation. Since diffusion-capillary mass transfer of liquid and vapor prevails significantly over convective transfer, the latter can be neglected. The coefficients of diffusion-capillary mass transfer can be considered constant during the entire heating time and uniformly distributed everywhere in the considered region of heat flow formation. We will also assume that heat losses above and below the heater installation interval can be neglected due to their smallness compared to the power of the supported heat flow. The length of the heater is considered to be so large that its dimensions affect the distribution of heat in the middle part of the heating interval. The formulated assumptions imply the heating of a fine-pored collector. The considered thermophysical characteristics in the middle part of the heating interval can also be assumed to be radially and axially symmetrically distributed in the plane. This reduces the mathematical formulation of the problem to a one-dimensional problem in which it is necessary to determine their nonstationary radial distributions.

This model allows for more accurate prediction of heat distribution in the reservoir, including phase transitions and diffusion-capillary effects. As a result, it is possible to more accurately estimate the temperature field, well flow rate after treatment, and duration of formation cooling.

As a result of such assumptions, the thermophysical characteristics of the formation can be considered as dependent on the radius r and time t: $T = T(r, t)$, $p = p(r, t)$, and $\theta = \theta(r, t)$. Their values at the initial moment of time are considered constant: $T(r, 0) = T_0$, $p(r, 0) = p_0$, and $\theta(r, 0) = \theta_0$.

For the convenience of the mathematical formulation of the model, we introduce such dimensionless parameters as dimensionless temperature:

$$T^* = \frac{T - T_0}{T};$$

dimensionless saturation of the liquid phase:

$$\theta^* = \frac{\theta_0 - \theta}{\theta_0};$$

dimensionless pressure resulting from the evaporation of the saturating liquid:

$$p^* = \frac{p - p_0}{p_0};$$

dimensionless radius:

$$R = \frac{r}{h};$$

dimensionless time (Fourier number):

$$Fo = \frac{\chi t}{h^2},$$

where χ is the thermal diffusivity (considered a constant value):

$$\chi = \frac{\lambda}{c\rho_e}.$$

Taking into account the above assumptions, the system of heat and mass transfer equations (1), (4), and (7) can be written in dimensionless form

$$\frac{\partial T^*}{\partial Fo} = \frac{\partial^2 T^*}{\partial R^2} + \frac{1}{R}\frac{\partial T^*}{\partial R} + \varepsilon \Pi_1 \frac{\partial \theta^*}{\partial R}, \quad (8)$$

$$\frac{1}{Lu}\frac{\partial \theta^*}{\partial Fo} = \frac{\partial^2 \theta^*}{\partial R^2} + \frac{1}{R}\frac{\partial \theta^*}{\partial R} + \Pi_2 \left(\frac{\partial^2 T^*}{\partial R^2} + \frac{1}{R}\frac{\partial T^*}{\partial R} \right), \quad (9)$$

$$\frac{\partial p^*}{\partial Fo} = -\frac{\varepsilon}{\Pi_3}\frac{\partial \theta^*}{\partial Fo}, \quad (10)$$

where $Fo > 0$ and $R > 0$ are the dimensionless time and radius, respectively; and Π_1, Π_2, Π_3, and Lu are the dimensionless coefficients described below. These quantities characterize the effect of mass transfer on the distribution of heat flows and vice versa, i.e., the effect of temperature on the saturation distribution. In particular, the Lykov criterion, defined as

$$Lu = \frac{a}{\chi \rho_e}$$

characterizes the intensity of diffusion-droplet mass transfer relative to diffusion heat transfer. If $Lu > 1$, then the thermal field due to diffusion-droplet mass transfer spreads faster than due to molecular thermal conductivity. In water-saturated sand and clay environments, its values are in the range of 0–3; in oil-saturated sands, $Lu \approx 1$.

The coefficient Π_1 defined as

$$\Pi_1 = \frac{mq\rho\Delta\theta}{c\Delta T}$$

characterizes the relationship between the amounts of heat spent on evaporation of the saturating liquid and on heating the formation (ΔT and $\Delta\theta$ are small changes in temperature and saturation in the volume element of the formation, respectively). In water-saturated sandy and clayey environments, its values are in the range 0.3–12.

The coefficient Π_2 defined as

$$\Pi_2 = \delta \frac{\Delta T}{\Delta \theta}$$

characterizes the increase in saturation $\Delta\theta$ due to a change in temperature by an amount ΔT. In water-saturated sandy and clayey environments, its values are in the range 0.1–0.9.

The coefficient Π_3 defined as

$$\Pi_3 = \beta \frac{\rho_e \Delta p}{\rho \Delta \theta},$$

characterizes the increase in saturation $\Delta\theta$ due to a change in pressure by an amount Δp. In water-saturated sandy and clayey environments, its values are in the range 0.2–0.7.

Equations (8)–(10) are supplemented by the initial conditions:

$$T^*\big|_{Fo=0} = 0, \ \ \theta^*\big|_{Fo=0} = 0, \ \ p^*\big|_{Fo=0} = 0, \quad (11)$$

as well as boundary conditions on the well axis:

$$\left.\frac{\partial T^*}{\partial R}\right|_{R=0} = -\frac{N}{2\pi\lambda}, \quad \left.\frac{\partial \theta^*}{\partial R}\right|_{R=0} = 0, \qquad (12)$$

and at infinity:

$$\left.T^*\right|_{R\to\infty} = 0, \quad \left.\theta^*\right|_{R\to\infty} = 0, \quad \left.p^*\right|_{R\to\infty} = 0. \qquad (13)$$

Here, since the heat flux on the heater axis is considered constant, N/λ = const (12); moreover, the condition for the derivative of saturation corresponds to a constantly preserved maximum value of saturation being maintained on the well axis.

Thus, initial boundary value problem (8)–(13) is a mathematical formulation of the model of thermophysical processes in an oil reservoir during heating of a shut-in well. In order to solve this problem, a numerical algorithm and software package implementing it were developed.

3. DEVELOPMENT OF A COMPUTER IMPLEMENTATION OF THE MODEL

For the computer implementation of the model, an algorithm has been developed for solving the initial–boundary value problem for the system of equations (8)–(10) under boundary conditions (11)–(13) using finite-difference approximations of partial derivatives. Both explicit and implicit schemes with stability condition analysis were implemented.

The computer implementation of the model was carried out in the Python programming language using the NumPy (for working with data arrays and solving systems of equations) and Dash (for visualization of calculation results). The developed application consists of the following main components: data input module, equation system solution module, output and solution visualization module.

The module for solving a system of differential equations describing the thermal effect on a reservoir is implemented using finite-difference schemes.

The application also contains a data processing subsystem required to transform the data obtained from the equation solving module. First, explicit and implicit objects are generated to represent the equation solving strategies. Then, a solution method is called for each object using an appropriate technique to solve the system of equations. The program has the ability to output graphs displaying the results of calculations using explicit and implicit schemes. Each graph shows curves of temperature, saturation, and pressure. By switching between studying the curves and comparing data for the schemes, the user is able to better understand the processes occurring during thermal stimulation of the reservoir.

The application controls allow the user to view and analyze the results of solving equations using explicit and implicit methods in real time. Such controls allow setting several constants, including steps and integration limits for time and space variables. Using a drop-down list, the user can select output functions (temperature, saturation, and pressure), while the values of the control parameters are adjusted via interactive sliders. A specific value for another variable can be selected along with the variable (temporal or spatial) to build a graph of the distribution of thermophysical characteristics. The program provides the user with flexibility in setting up parameters by placing a panel with control elements on the left side of the main page and concentrating all settings in one screen location.

The set of sliders and drop-down menus is a component of the settings panel. A variable (temporal or geographic) can optionally be specified to serve as the basis for the abscissa axis of the graphs. Sliders may be used to change the numerical values of the 3 control parameters that affect the process. Another slider allows one to select the value of the spatial or temporal variable for visualization. The application interface tool is used to study the behavior of the distribution (temperature, saturation, or pressure) based on time or spatial variables. To achieve this goal, a graph can be produced with the values of the function under study plotted on the ordinate axis and the time or spatial variable plotted on the abscissa axis. In this case, the slider in the settings panel can be used to fix a certain value of the other variable. The resulting graphs display changes in the pressure, saturation, and temperature functions as a function of the spatial variable when the time variable is fixed. This focuses attention on how one variable, such as time or spatial coordinate, affects fixed parameters that are determined by another.

4. RESULTS AND DISCUSSION

As a result of numerical modeling using the developed software package, radial distribution curves were obtained (Fig. 1) along with time dependencies (Fig. 2) of temperature and saturation (by virtue of Eq. (10). A separate analysis of pressure does not make sense, since the corresponding dependencies are similar to saturation).

The dependencies of these quantities on the radius (Fig. 1) can be used to identify features of the spatial distribution of thermophysical characteristics. In particular, with increasing distance from the center, the temperature, saturation, and pressure decrease with a gradual slowdown. However, these radial dependencies of temperature and saturation are of different natures.

The temperature drops fairly quickly at small radii. Then its decrease slows down and gradually stops, reaching an equilibrium value already at relatively small values of the ratio of the radius to the length of the heater. Saturation (and pressure, by analogy) at small radii begins to decrease slowly, then quickly fall, and finally, at large distances, it reaches an equilibrium value and stops changing. This difference is due to the fact that the heat flow on the heater axis is maintained constant, and there is no saturation gradient on this axis.

The time dependencies of these quantities (Fig. 2) are used to identify the kinetic features of thermophysical processes. In particular, over time, temperature, saturation, and pressure increase with a gradual slowdown. However, at different radii, these dependencies are of a different nature. At small radii and short times, a sharp increase in temperature, saturation, and pressure is observed, followed by a rapid decline in the growth rates of these quantities. At large radius values, temperature, saturation, and pressure at first remain practically unchanged and then begin to grow slowly, gradually gaining growth speed. Such patterns correspond to upward convex sections of kinetic curves (at $R = 1$) and concave sections (at $R = 2$ and 3) on Fig. 2.

The parameters Π_1 and Π_2 are the most important in the model under consideration. They affect the saturation functions θ^* and temperature T. Varying these parameters implies actually going through different environments of the bed. Therefore, they are selected as the controlling thermophysical parameters of the model to evaluate the characteristics of processes in different soils.

If we accept $\Pi_1 = \Pi_2 = 0$, then this corresponds to the absence of mass transfer in the thermal physics problem. Vakhitov and Simkin [16] indicated that the mass transfer accounting leads to an increase in the radius of thermal influence, which, in turn, leads to higher calculated values of the formation cooling duration and an increase in flow rate after treatments. In accordance with the condition of maintaining thermal balance, an increase in the radius of thermal influence leads to a decrease in temperature on the wall and in the immediate vicinity of the well.

Heat transfer through a porous medium is controlled by the parameter Π_1, which reflects the effect of the saturation gradient on temperature change. This parameter is involved in Eq. (8), which describes the temperature change. As indicated by a higher value of Π_1, an increase in the rate of temperature change can be the result of an increase in the heat flow passing through the porous medium. The effect of the saturation gradient on temperature change is stronger the higher the value of Π_1.

The value of saturation is more significantly affected by the parameter Π_2. In addition, Π_2 affects temperature changes. The coefficient Π_2 associated with the influence of the temperature gradient on the change in saturation is included in the equation for saturation (9). The influence

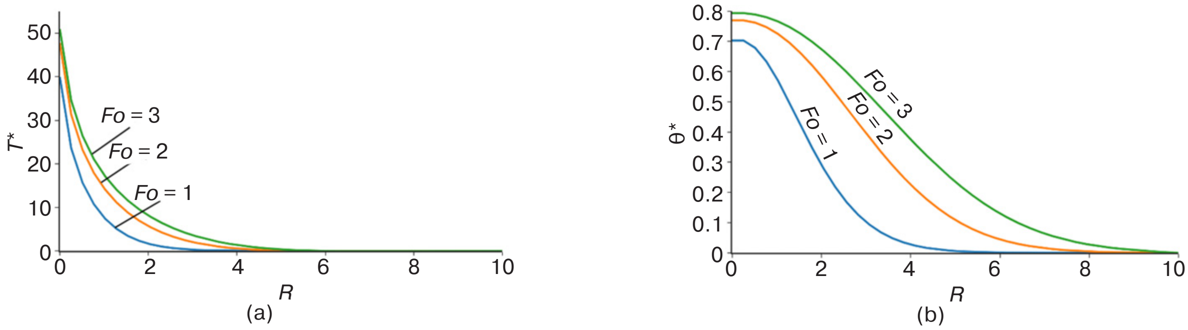

Fig. 1. Radial distributions of (a) temperature and (b) saturation at $\Pi_1 = 10$, $\Pi_2 = 0.1$, $\Pi_3 = 0.5$, Lu = 1, e = 0.28, l = 2.49 W/(m·K), and N = 1000 W/m

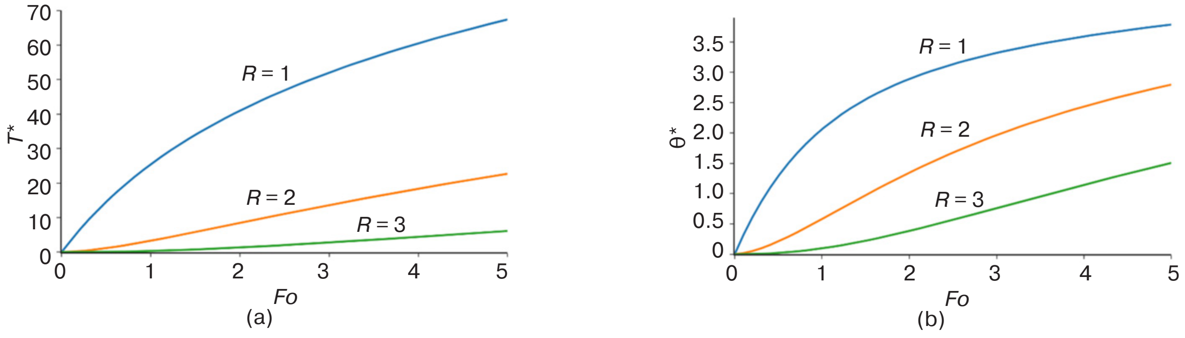

Fig. 2. Curves of (a) temperature kinetics and (b) saturation at parameter values as in Fig. 1

of the temperature gradient on the change in saturation is greater the higher the value of Π_2.

Thus, in the model, the parameters Π_1 and Π_2 determine the degree of relationship between temperature T^* and saturation θ^*. When modeling cooling after switching off the heater, these parameters can be used to adjust the degree of relationship between these two variables.

The results of the conducted series of numerical experiments were used to identify patterns of influence of control parameters on spatial distributions and kinetics of thermophysical characteristics. The influence of parameter Π_1 on temperature and saturation is illustrated in Figs. 3 and 4. An increase in the value of Π_1 leads to a more noticeable change in the saturation distribution along the radial coordinate than in temperature. From the point of view of the model structure, this is due to the fact that Π_1 is part of the coefficient in Eq. (1) for the derivative of saturation θ^* along the radial coordinate R. The radial distribution of saturation shifts more smoothly at large distances from the well and more steeply near it (small values of the radial coordinate R) as Π_1 increases. The saturation gradient has a greater effect on temperature fluctuations with an increase in Π_1, which can lead to a more rapid change in temperature in areas with a strong saturation gradient. From the physical point of view, sorting through the values of Π_1 corresponds to that of various fields in which the density and porosity of the soil and oil differ.

The simulation results shown in Fig. 3 show that a thousand-fold increase in the value of the parameter Π_1 leads to a very slight decrease in temperature (Fig. 3a) and a slight increase in saturation (Fig. 3b), which depends on the distance from the heater axis at a fixed point in time. Consequently, the obtained results indicate that the porosity and density of the soils and the liquid phase of the formation have little effect on the spatioradial distribution of temperature, saturation, and pressure in the formation.

The kinetic curves obtained as a result of modeling (Fig. 4) show that a thousand-fold increase in the value of the parameter Π_1 leads to an insignificant decrease in temperature (Fig. 4a) and an insignificant increase in saturation (Fig. 4b) at a fixed distance from the heater axis. Since this difference increases with increasing time, the influence of the porosity and density of soils and the liquid phase of the formation on the kinetics of temperature, saturation and pressure in the formation also begin to be noticeable at long time durations.

Physically, the enumeration of the values of Π_2 corresponds to the enumeration of various values of

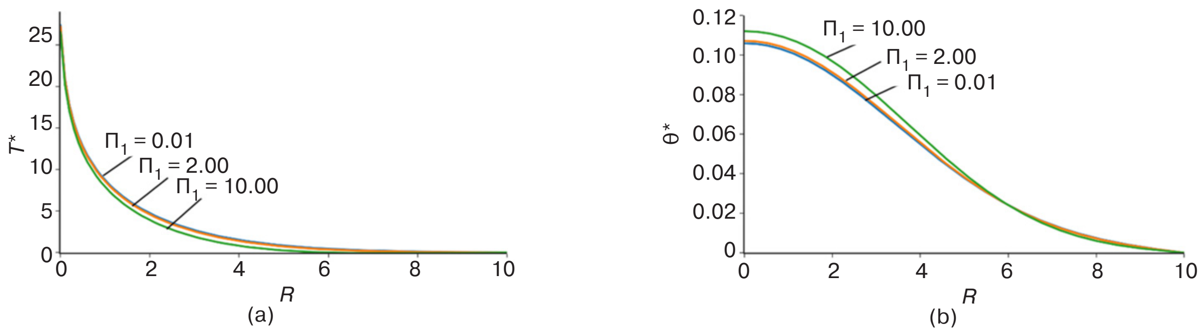

Fig. 3. Radial distributions of (a) temperature and (b) saturation at different values of the parameter Π_1 and fixed Fo = 2 (the other parameter values are the same as in Fig. 1)

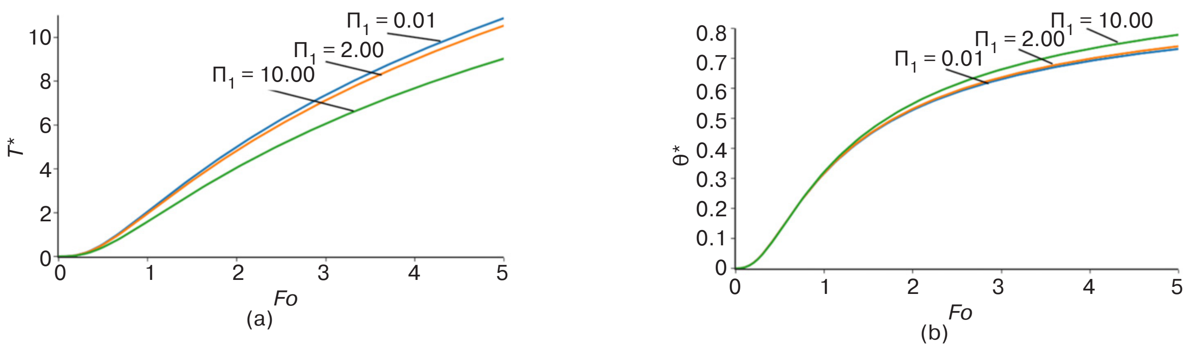

Fig. 4. Curves of (a) temperature kinetics and (b) saturation at different values of the parameter Π_1 and fixed R = 2 (the other parameter values are the same as in Fig. 1)

the thermogradient coefficient δ, which characterizes the transfer (flow) of moisture in the liquid phase of the oil-bearing formation. The modeling results (Fig. 5) show that a thousand-fold increase in the value of the parameter Π_2 leads to a very insignificant decrease in temperature (Fig. 5a), but to a significant increase in saturation and pressure (Fig. 5b) depending on the distance from the heater axis at a fixed point in time. An increase in the value of Π_2 leads to more rapid changes in the radial distribution of temperature T^* and saturation θ^*. The distributions of T^* and θ^* shift more smoothly at large distances from the well and more sharply near it as Π_2 increases. While saturation changes slightly at small Π_2, the saturation of the liquid phase of the oil formation begins to depend strongly on the distance from the heater axis at values of the thermogradient coefficient corresponding to water-saturated sands and clays.

Figure 6 illustrates the influence of the thermogradient coefficient, which can be used to evaluate the effect of moisture transfer in the liquid phase of the formation under the action of a temperature gradient in non-isothermal conditions on the kinetics of temperature and saturation. The growth of the thermogradient coefficient in the interval corresponding to water-saturated sands and clays leads to a noticeable decrease in temperature and an increase in the saturation of the liquid phase of the oil formation in such soils.

The influence of the elasticity coefficient of the vapor–gas mixture in the reservoir and the ratio of the skeleton and liquid phase densities are both characterized by the variation of the value of the parameter Π_3. This influence is particularly significant with regard to pressure (Fig. 7). The simulation results show that an increase in the value of the parameter Π_3 leads to a decrease in pressure in general. Although this decrease is almost imperceptible at short times, it becomes very noticeable at long times given a fixed distance from the heater axis (Fig. 7a). The same significant decrease with an increase in the elasticity coefficient of the vapor–gas mixture is observed at short distances from the heater axis at a fixed point in time (Fig. 7b). At large distances from the heater axis, a change in the parameter Π_3 ceases to affect the pressure in the reservoir.

The influence of the intensity of diffusion-capillary mass transfer relative to the diffusion heat transfer in the reservoir is characterized by the variation of the Lykov criterion *Lu*. Figure 8 shows the dependencies of the kinetics and radial distribution of saturation with variation of this criterion. The modeling results show that an increase in the value of the Lykov criterion leads to a sharp increase in saturation even at short

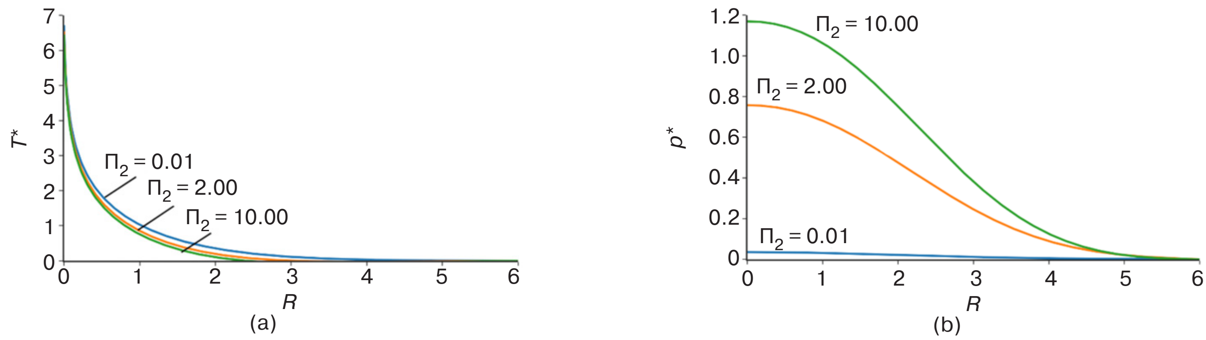

Fig. 5. Radial distributions of (a) temperature and (b) saturation at different values of the parameter Π_2 and fixed *Fo* = 2 (the other parameter values are the same as in Fig. 1)

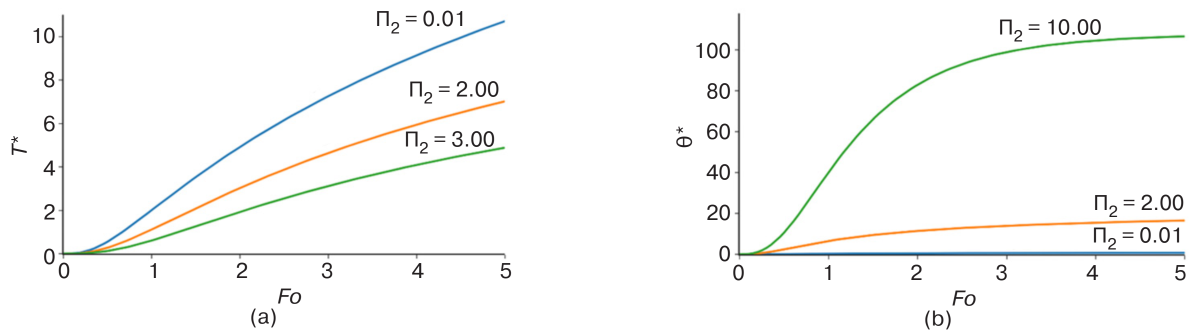

Fig. 6. Curves of (a) temperature kinetics and (b) saturation at different values of the parameter Π_2 and fixed *R* = 2 (the other parameter values are the same as in Fig. 1)

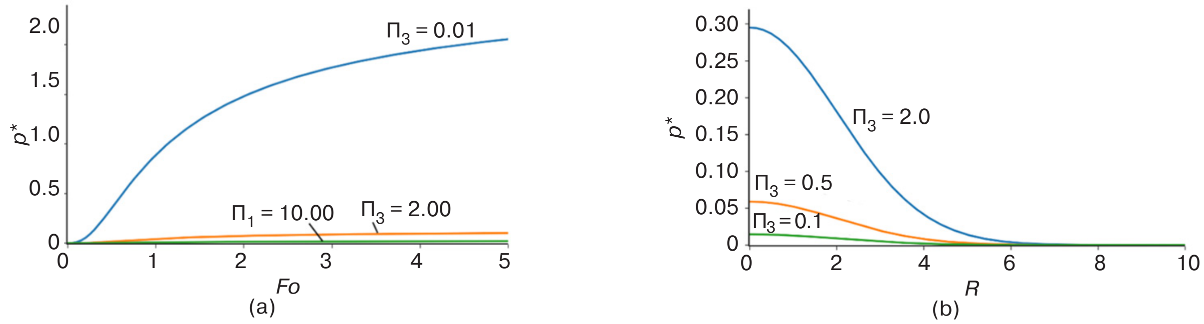

Fig. 7. Curves of (a) kinetics and (b) radial pressure distribution at different values of parameter Π_3 and fixed (a) $R = 2$ and (b) $Fo = 2$ (other parameter values as in Fig. 1)

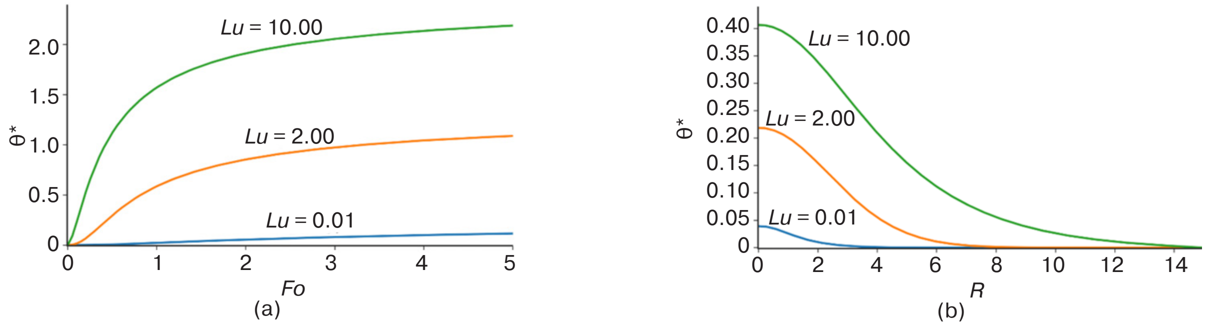

Fig. 8. Curves of (a) kinetics and (b) radial distribution of saturation at different values of the parameter *Lu* and fixed $R = 2$ (a) and (b) $Fo = 2$ (the remaining parameter values are the same as in Fig. 1)

times (Fig. 8a). An increase in the intensity of diffusion-capillary mass transfer relative to the diffusion heat transfer in the reservoir leads to an increase in saturation at a fixed point in time at short distances from the heater axis (Fig. 8b). At large distances from the heater axis, a change in the intensity under consideration does not affect saturation.

It should be noted that the variation of the Lykov criterion has virtually no effect on the temperature profiles. A slight decrease by fractions of a unit (in dimensionless temperature units T^*) was observed only at fairly long times (about 5 units in dimensionless time units of *Fo*).

Such a model parameter as the heat flow on the heater axis, as determined according to Eq. (12) by the ratio N/λ, also affects the value of the thermophysical characteristics but only as a numerical multiplier, i.e., temperature, saturation, and pressure are directly proportional to the specific heat flow on the heater axis.

CONCLUSIONS

The paper examines a mathematical model that describes the patterns of thermophysical processes in a formation during heating while taking into account the diffusion-capillary mass transfer of liquid and steam. The model, which provides a description of the occurring physical phenomena, takes into account the complex interaction of heat transfer processes and changes in the saturation of the liquid phase and pressure.

Software for the computer implementation of the model was developed using Python libraries (Pandas, Dash, NumPy) to provide convenient visualization and analysis of the modeling results. The inclusion of various modules for the numerical solution of the thermophysical initial–boundary value problem allows the selection of solution algorithms according to explicit or implicit schemes, along with discretization steps and other parameters for optimizing the computational procedure. The software contains a convenient user interface for entering parameters, displaying results in the form of tables and graphs, and exporting data.

Using the developed software, numerical experiments were conducted to study how various factors, such as reservoir properties, heater characteristics, and initial and boundary conditions, affect the reservoir cooling process. The analysis and interpretation of results showed that the spatial temperature distribution profile decreases quite quickly at small radii, followed by a slowdown in the decrease to an equilibrium value. The spatial saturation and pressure distribution profiles decrease at small radii and reach equilibrium values at large distances. Over time, the considered thermophysical characteristics monotonically increase.

It is shown that the porosity and density of soils and the liquid phase of the reservoir have a weak effect on the spatial distributions of temperature, saturation, and pressure in the reservoir. The influence of the porosity and density of soils and the liquid phase of the reservoir on the kinetics of these thermophysical characteristics is clearly noticeable at long time durations.

The results of the modeling showed that the saturation changes slightly at small values of the thermogradient coefficient; however, at values corresponding to water-saturated sands and clays, the saturation of the liquid phase of the oil reservoir begins to depend strongly on the distance from the heater axis. The growth of this coefficient in this range leads to a noticeable decrease in temperature and an increase in the saturation of the liquid phase of the oil reservoir in such soils.

It is confirmed that an increase in the coefficient of elasticity of the steam–gas mixture leads to a decrease in pressure at short distances from the heater axis, but that at long distances, the pressure stops changing. An increase in the intensity of diffusion-capillary mass transfer relative to the diffusion transfer of heat in the reservoir leads to a sharp increase in saturation at short distances from the heater axis; however, at longer distances, the saturation stops changing.

The results of this work may be useful for the oil industry when it is necessary to understand the patterns of thermal physical processes in the formation during heating to create more effective methods of managing the production process as a means of increasing its profitability. The proposed model and its analysis also expand the understanding of the possibilities of using mathematical and computer modeling of processes in the oil industry.

Authors' contributions

S.E. Savotchenko—problem statement, formulating the model, deriving equations, analyzing the results, writing the text of the article.

V.A. Zakharov—discretization of the model, developing the algorithm for a numerical method, developing the software for the model, computer experiments, and visualization.

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