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NUMERICAL SIMULATION OF HIGH-PERMEABILITY WATERFLOODED SUBLAYER WATER SHUT-OFF UNDER UNCERTAINTY OF ITS LOCATION IN A PETROLEUM RESERVOIR

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A B S T R A C T

The paper explores the optimal placement of the chemical blocking agent (water shut-off material) in a high-permeability watered sublayer under uncertainty of its geometry in the inter-well area. The simulation of the water flooding process at different sublayer positions and variations of blocking agent placement was performed using a high-speed computing two-dimensional model of stream tube. The decision of the optimal placement of the water shut-off agent was made using probabilistic processing of the results without using a large amount of resource-intensive numerical simulation. The relationship between the optimal water shut-off scenario and the sublayer geometry is demonstrated. The relationship between the parameters of the sublayer geometry distribution function and the probabilistic behavior of the generalized efficiency has been established. Simulations are performed for various mobility ratios: in cases with equal viscosity liquids and typical ones for reservoirs in the Volga region and Western Siberia.

Keywords: petroleum reservoir; high-permeability layer; geological uncertainty; early water breakthrough; water shut-off; stochastic modeling; two-phase flow; model of stream tube.

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Introduction

The process of petroleum extraction is associated with significant risk, particularly due to uncertainty of geological parameters of oil reservoir. Decision-making regarding financial and economic assessments in this field relies heavily on the uncertain parameters of the geological model of the deposit [1]. Complications arise when high-permeability layers, prone to early water breakthrough, are present in the oil reservoirs. One of the available methods to solve this problem is the use of fixed-type shielding technologies with a low level of destruction based on resins, silicates, or polymers. This can be utilized to increase the efficiency of water shut-off in high-permeability layers and increase the reservoir coverage during waterflooding processes [2].

When using computationally expensivethree-dimensional models, instead of stochastic modeling designed for conditions of uncertainty in the initial data, one is usually limited to the most probable deterministic model. Comparative calculations on such models can show the qualitative behavior of the water shut-off treatment for different types of geological structure of the formation [3, 4]. At the same time, to obtain quantitative estimates of optimal blocking options from a probabilistic viewpoint, it is necessary to carry out multivariate stochastic modeling [5]. To investigate potential solutions, this research explores the relationship between the parameters of the distribution function of the characteristics of the high-permeability sublayer shape and the probabilistic behavior of the efficiency indicator in an inter-well space with uncertain highly permeable water-cut interlayers.

To demonstrate the possibility of fast simulation, this work uses a two-dimensional flow model using a fixed stream tube. Variable width of stream tube corresponds to the case of a five-point water flooding system [6-9]. Calculations were performed for the ratio of the viscosity of the water phase to the viscosity of the oil phase, specifically 1/1 in the model case and 1/6 in the typical case for terrigenous reservoirs in the Volga region and Western Siberia [10]. It must be noted that simulation of the process of blocking agent placing requires the formulation and solution of individual problems of multiphase multicomponent flow [3, 4, 11], was not modeled and is not included in this research.

Method

The section of the reservoir is being considered, which constitutes an element of the waterflooding five-spot pattern arrangement of vertical wells (fig.1a) [12].

The vertical location of the high-permeability layer at the boundaries of the stream tube can be determined through geophysical investigations of wells along the inflow profile, and thereby is known. For specificity, it will be assumed that the high-permeability layer passes through the middle of the reservoir cross-section in the wells. The layer's width will be considered constant and equal to 10% of the total thickness of the reservoir, which itself is 10 times smaller than the distance L between wells along the stream tube.

The effect of the parameter $\xi = OO'$ – the magnitude of the deviation of the middle of the high-permeable layer from the center of the reservoir, is investigated (fig.1b). It is assumed that the high-permeable layer passes along an arc of a circle,

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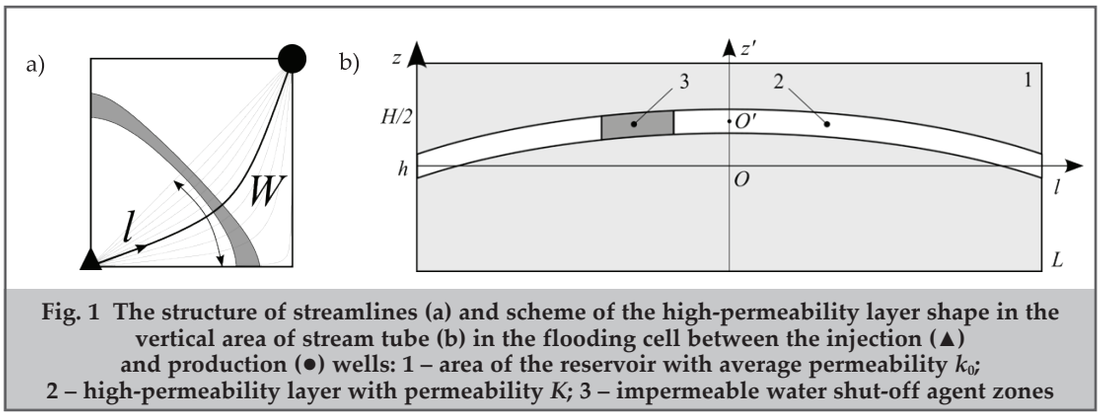

Fig. 1 The structure of streamlines (a) and scheme of the high-permeability layer shape in the vertical area of stream tube (b) in the flooding cell between the injection (▲) and production (●) wells: 1 – area of the reservoir with average permeability k_0; 2 – high-permeability layer with permeability K; 3 – impermeable water shut-off agent zones

and that the deviation ξ does not exceed a one-quarter of the total height H of the reservoir and is a random variable with a known distribution function F_ξ.

The waterflooding process is modeled according to the flow model in a vertical area of a fixed stream tube [7, 8] for a set of values $\{\xi_j\} = \{0; H/16; H/8; 3H/16; H/4\}$. The normalized equations of the two-dimensional problem of two-phase flow in the cross-section of a stream tube are written neglecting formation and fluid compressibility, gravity force, and capillary effects. Compressibility effects can be neglected, since their duration is two orders of magnitude shorter than the duration of the simulated displacement process and they end already at the beginning of this process. The contribution of capillary forces with typical parameters of the reservoir system turns out to be significant only at the displacement front, the length of which is negligibly small compared to the size of the flooding area [13]. Gravity effects are not considered, assuming that the densities of the water and oil phases differ by less than 10%. This system of equations has the following form

$$\frac{1}{W}\frac{\partial}{\partial l}\left(W\sigma\frac{\partial p}{\partial l}\right)+\frac{\partial}{\partial z}\left(\sigma\frac{\partial p}{\partial z}\right)=0,$$

$$m\frac{\partial S}{\partial t}+\frac{1}{W}\frac{\partial\left(Wuf\right)}{\partial l}+\frac{\partial\left(vf\right)}{\partial z}=0,$$

$$\mathbf{u}=(u,v),\ u=-\sigma\frac{\partial p}{\partial l},\ v=-\sigma\frac{\partial p}{\partial z},\ \sigma=k\varphi,$$

$$\varphi=f_1+K_\mu f_2,\quad f=f_1/\varphi,\quad K_\mu=\mu_1/\mu_2,$$

where l, z – the longitudinal and vertical coordinates in the vertical stream tube section; $W(l)$ is a function of the relative cross-sectional area of the stream tube; t – time; p – pressure in the fluid; S – water saturation; $\mathbf{u}$ (u, v) are the vector and components of the Darcy velocity of a two-phase mixture; f_i – functions of relative phase permeability; μ_i – dynamic viscosity; subscripts 1 and 2 correspond to the water and oil phases, respectively; k is the normalized absolute permeability.

The average permeability of the reservoir is $k_0 = 1$. The area of the high-permeability layer Ω with permeability $K = 100k_0$ contains the fixed water shut-off subarea Δ with permeability $k_1 = 10^{-6}$ (fig. 1). So, the permeability field is given as follows

$$k(l,z)=\begin{cases}k_0,\ (l,z)\notin\Omega,\\ K,\ (l,z)\in\Omega\setminus\Delta,\\ k_1,\ (l,z)\in\Delta.\end{cases}$$

The functions of relative phase permeabilities are given in the form of power dependences on the effective water saturation s:

$$f_1=s^3,\ f_2=\left(1-s\right)^3,\ s=\frac{S-S_*}{S^*-S_*},$$

where S^*, S_* are the water saturation endpoints.

The upper and lower reservoir boundaries are impermeable:

$$0\le l\le L,\ z=0,\ z=H:\ \frac{\partial p}{\partial z}=0.$$

The left and right boundaries of the stream tube section are adjacent to the injection I and production P wells, respectively, and the boundary conditions on them simulate the waterflooding process at given constant pressures p_I and $p_P < p_I$ on the wells:

$$l=0,\quad 0\le z\le H:\ \ s=1, p=p_I;\quad l=L, 0\le z\le H:\ \ p=p_P.$$

The function of the relative cross-sectional area of the stream tube $W(l)$ is defined as the width of the effective stream tube between regular five-point wells system [14]:

$$W\left(x\right)=\frac{w\left(x\right)}{w_R}=\begin{cases}1+Ax, 0\le x\le 0.5;\\ 1+A\left(1-x\right), 0.5\le x\le 1;\end{cases}\qquad x=l/L.$$

For the intrinsic dimensional values of the well radius $r_w \sim 0.1m$ and the distance between the rows of injection and production wells $D \sim 100m$, the values of the effective stream tube length $L \sim 150m$ and coefficient $A = 1616$.

At the initial state, there is no mobile water phase in the reservoir:

$$t=0:\ s=s_0=0.$$

Numerical simulation was performed on a finite-volume computational grid containing 60 vertical blocks and 600 horizontal blocks.

After the water breakthrough to the production well through the high-permeability layer and the water cut reaches 50% from the time point t_0, the second stage of waterflooding is simulated. At this stage, fixed impermeable areas are defined within the high-permeability layer, corresponding to the location of the blocking agent. Injection of gel material into a high-permeability layer should be performed after its flooding in order to more fully extract the oil reserves [15]. The water shut-off treatment of the high-permeability sublayer is determined by only one parameter – the relative distance from the injection well to the beginning of the isolated interval (fig. 1). The volume of the blocking agent is 10% of the total volume of the high-permeability layer. The length of the isolated interval is calculated according to the

local width of the stream tube.

The distinctive feature of the examined placement of water shut-off material is its remote positioning from injection wells. The advantages of such deep placement are explained by a more efficient redistribution of injected water flow between layers and by the presence of high-pressure gradients near the injection wells, which can damage the blocking material [16]. Previously, the technical implementation of deep placement was considered difficult or impossible. To overcome these difficulties, new gel systems are being developed, and their practical application possibilities are being thoroughly investigated. Based on experimental data and modeling results [17], the examined gel system allows for the control of packer operation and delays gel formation for weeks to several months or years. These indicators enable the placement of gel systems at greater distances from wells and the implementation of more complex scenarios for local permeability alteration.

Results and discussion

When analyzing the simulation results, the following indicators are used

- oil recovery factor:

$$E(t)=1-\frac{V_2(t)}{V_2(0)}=1-\frac{\int_0^H\int_0^L\left[1-s(t,l,z)\right]W(l)dl\,dz}{\int_0^L H\left[1-s_0\right]W(l)dl},$$

- pore volumes:

$$PV(t)=\frac{Q(t)}{V_P}=\int_0^t q(t)dt\Big/\int_0^L w_L hmW(l)dl, \quad (1)$$

- water cut on the producing well:

$$F(t)=q_1(t)/q(t). \quad (2)$$

Here

- liquid injection rate:

$$q(t)=w_L\int_0^h u(t,L,z)dz, \quad (3)$$

- water producing rate:

$$q_1(t)=w_L\int_0^h f(t,L,z)u(t,L,z)dz, \quad (4)$$

where w_L is the true cross-sectional area of the stream tube on the surface of the well, simplified by substituting (3), (4) into (1) and (2) and thus does not require setting when calculating the relative values F and PV; V_P is the pore volume of the stream tube.

To minimize the quantity of pore volumes injected PV and maximize the oil recovery factor E, a generalized efficiency indicator dependent on the parameters d, ξ was considered:

$$\theta(d,\xi)=\gamma E(T;d,\xi)-(1-\gamma)PVI(T;d,\xi),$$

where γ represents the operational-economical weighting coefficient.

As a result of a series of computational experiments, a set of values $\theta_{i,j}=\theta(d_i,\xi_j)$ was obtained, where i is variant number of the gel placement, j is implementation number of the layer geometry. The set of these values was approximated by the function

$$\Theta(d,\xi)=\theta_{\min}+c(d)\Delta\theta\left(1-e^{-\lambda(d)|\xi|}\right), \quad (5)$$

where $\Delta\theta=\theta_{max}-\theta_{min}$; $\theta_{min/max}$ – limit values of θ; λ, c are the approximating coefficients. The modulus of ξ was used in equation (5) since this function is even with relation to positive and negative layer deviations from the horizontal due to the symmetry of the modeled process.

From the condition that ξ is a continuous random variable with a known cumulative distribution function F_ξ, for which there is a probability density function (PDF) f_ξ, the PDF of the quantity $\Theta(d,\xi)$ can be found f_Θ for each fixed d:

$$f_\Theta(x)=\left[f_\xi\left(\Theta^{-1}(x)\right)+f_\xi\left(-\Theta^{-1}(x)\right)\right]\frac{d\xi}{d\Theta}, \quad (6)$$

where $d\xi/d\Theta$ is calculated using (5).

When $K\mu$ = 1 the ten positions of the water shut-off agent placement were considered. Modeling of the second stage of water flooding continued until the water cut of the production well reached 98%. Based on the obtained values E (fig. 2a) and PV (fig. 2b), the generalized indicator θ with the coefficient γ = 0.993 (fig. 3) was calculated for various high-permeability sublayer geometries and the placement of the water shut-off material.

With given phase viscosity, the maximum efficiency was taken out with the same location of the water shut-off agent – d = 0.2 (fig.3). Approximation (5) was constructed for this parameter value d (fig. 4a).

Assuming that ξ obeys Gaussian law (fig. 4b) with the parameters $\mathbb{E}\xi=0$ – expected value, $\mathbb{D}\xi=\sigma^2$ variance, the form of f_Θ is determined by formula (6) (fig. 4c). The maximum value f_Θ indicates the most probable efficiency $\Theta^*(d)$ of the water shut-off treatment. The corresponding variation ξ^* is determined by dependence (5). In general, ξ^* may not coincide with the most probable one (in this case $\xi^*=\xi_0=0$) (fig. 4c). Also, using the PDF, the expected value Θ_* is calculated, which allows predicting the mean expected effect with the selected water shut-off scenario.

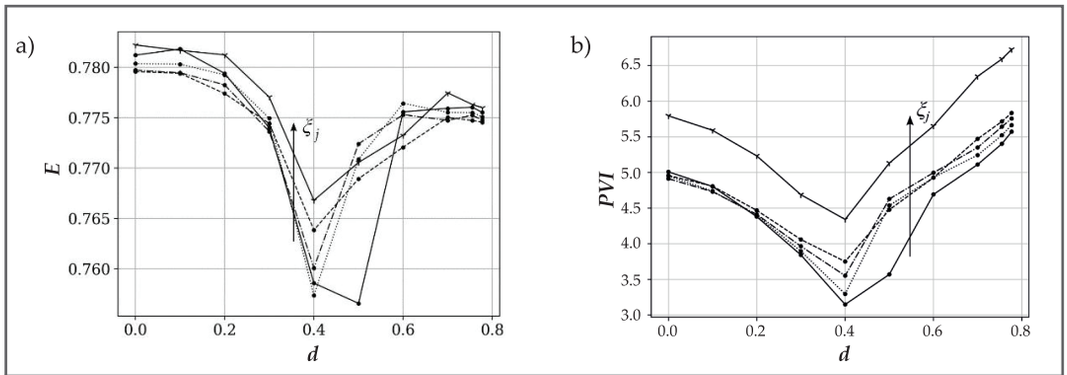

Fig. 2. Oil recovery factor (a) and the PV (b) for different values ξ_j depending on blocking agent placement

Therefore, depending on the parameters of the distribution of ξ, the most probable and mean expected outcomes of treatment differ from the result for the most probable position of the high-permeability sublayer (fig. 5). The acquired findings demonstrate that modeling the results of water shut-off treatments for a single most probable geological model under conditions of geological uncertainty allows for the calculation of only a pessimistic scenario, which, in turn, may not always be the most probable or expected scenario and impact the assessment of field development risks.

When $K\mu$ = 1/6 twelve positions of the blocking material placement were considered when the water flooding was continued until the water cut of the production well reached 95%. Based on the obtained values E (fig. 6a) and PV (fig. 6b), the generalized indicator Θ with the coefficient γ = 0.98 (fig. 7) was calculated for various high-permeability sublayer geometries and the placement of the blocking agent. Under these conditions, the optimal treatment depends on the sublayer's geometry.

The decision on the optimal placement of the water shut-off agent should be made taking into account the probabilistic behavior of the generalized efficiency coefficient, which depends on the parameters of the sublayer.

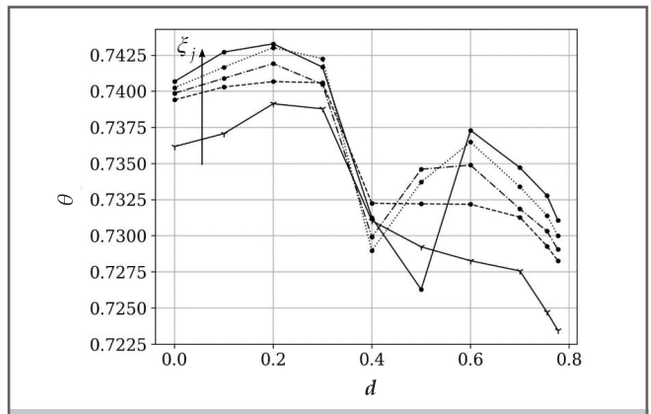

Fig. 3 The efficiency of the blocking agent placement at $K\mu$ = 1

Density functions of efficiency have been constructed for each water shut-off interval, where in the mathematical expectation, denoted as $\Theta_*(d)$, has been selected for various blocked intervals (fig. 8). Thus, a treatment scenario can be identified, facilitating the attainment of a statistically expected efficiency with a large number of strategy implementations under conditions of geological uncertainty.

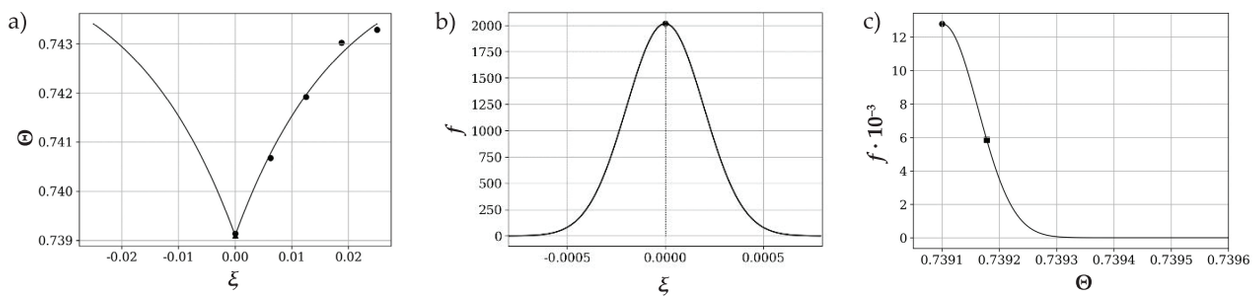

Fig. 4. Dependence of water shut-off efficiency on sublayer geometry, ● – values θ_{ij} (a), PDF of the deviation the high-permeability sublayer (b), effect PDF (c) at $\sigma^2 = 3.9 \cdot 10^{-8}$, (●) – most probable effect Θ*, (■) – mathematical expectation Θ_*

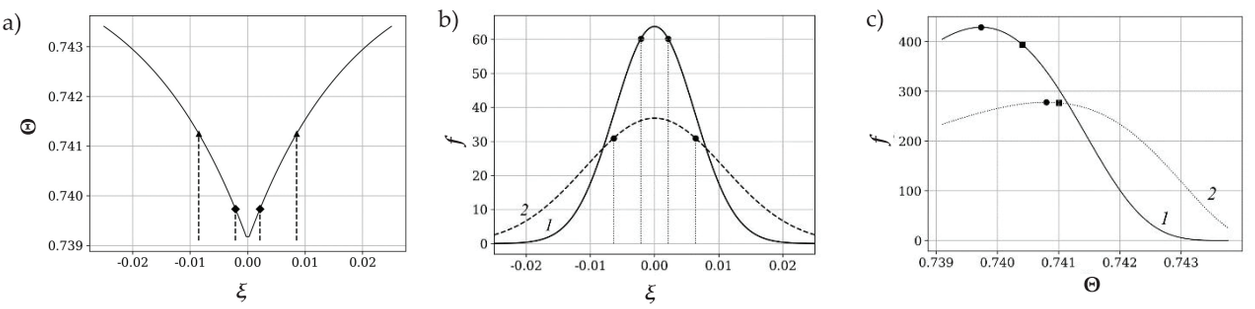

Fig. 5. Dependence of water shut-off efficiency on sublayer geometry (a), PDF of the deviation the high-permeability sublayer (b), effect PDF (c) at (1) – $\sigma^2 = 3.9 \cdot 10^{-5}$, (2) – $\sigma^2 = 3 \cdot 3.9 \cdot 10^{-5}$; (●) – most probable effect Θ* (■) – mathematical expectation Θ_*

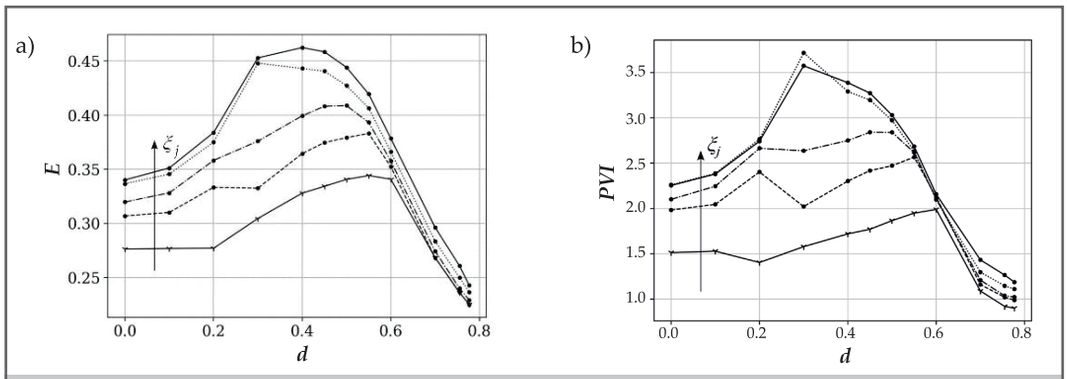

Fig. 6. Oil recovery factor (a) and the pore volumes injected (b) for different values ξ_j depending on the blocking agent placement

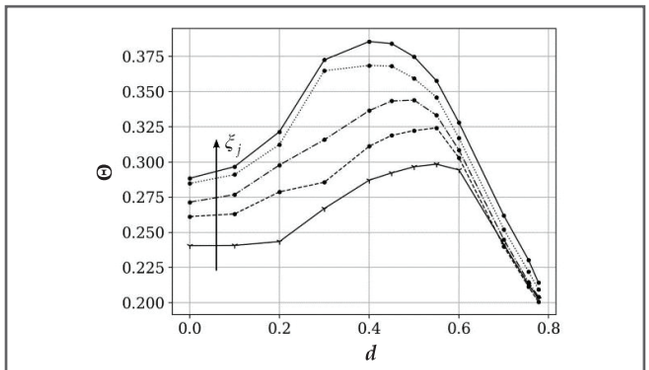

Fig. 7. The efficiency of the blocking agent placement at depending on the blocking agent placement $K\mu$ = 1/6

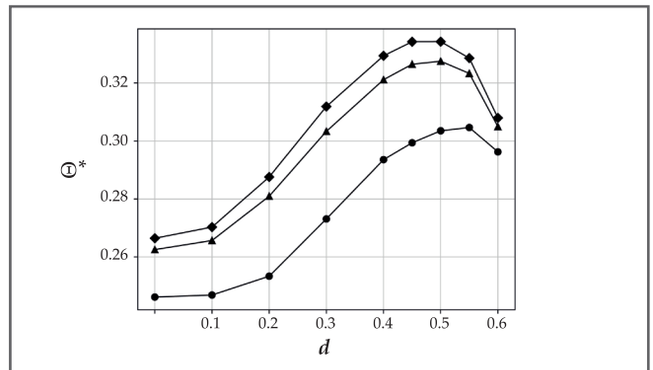

Fig. 8. Most probable efficiency for different water shut-off intervals at (●) – $\sigma^2 = 3.9 \cdot 10^{-6}$, (▲) – $\sigma^2 = 3 \cdot 3.9 \cdot 10^{-5}$, (♦) – $\sigma^2 = 7 \cdot 3.9 \cdot 10^{-5}$

Conclusion

This paper, probabilistic modeling based on a series of deterministic flow models has been performed to address the question of enhancing oil recovery under uncertainty in the shape of the high-permeability sublayer. An analytical-probabilistic approach and computationally efficient numerical simulation scheme for flow were employed. To accelerate the calculations, the traditional three-dimensional flow model was decomposed into two-dimensional problems in stream tubes vertical sections. Based on numerical calculations, a functional relationship is determined between the variable parameters and efficiency indicators. The final probabilistic forecast of efficiency and selection of the optimal treatment scenario is made almost instantly based on the given probabilistic parameters of the geological model without the need for the flow numerical simulation.

The findings demonstrate that modeling of water shut-off treatments for the most probable geological model under uncertainty in the geometry of the high-permeability sublayer allows only for a pessimistic scenario calculation, which may not always represent the most probable result of the series of actions. This can impact the assessment of the development of accumulation risks and lead to inappropriate decision-making.

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Численное моделирование изоляции обводненного высокопроницаемого слоя в условиях неопределенности его положения в нефтяном пласте

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Реферат

Исследовано оптимальное размещение изоляционного материала в высокопроницаемом обводненном пропластке, положение которого является неопределенным в межскважинном пространстве. Моделирование процесса заводнения для различных положений пропластка и интервалов расположения изоляционного материала выполнено с помощью быстродействующей двумерной модели фильтрации в трубке тока. Выбор оптимального расположения изоляции выполнен с использованием вероятностной обработки результатов без использования большого объема ресурсоемкого численного моделирования фильтрационных задач. Продемонстрирована зависимость оптимального способа изоляции от положения высокопроницаемого слоя. Установлена взаимосвязь между параметрами функции распределения геометрии пропластка и вероятностным поведением обобщенного показателя эффективности. Моделирование выполнено для различных показателей отношения вязкости: равновязких и характерных для месторождений Поволжья и Западной Сибири.

Ключевые слова: нефтяной пласт; высокопроницаемый слой; геологическая неопределенность; преждевременное обводнение; изоляция; стохастическое моделирование; двухфазная фильтрация; модель трубок тока.

Sulaşmış yüksək keçiricikli təbəqənin neft layında qeyri-müəyyən yerləşməsi şərtlərində həmin təbəqənin təcrid edilməsinin riyazi modelləşdirilməsi

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Xülasə

Yerləşməsi quyuarası fəzada qeyri-müəyyən olan yüksək keçiricikli sulaşmış laycıqda təcridedici materialın optimal yerləşdirilməsi tədqiq edilmişdir. Sürətli ikiölçülü cərəyan borucuğunda süzülmə modelindən istifadə edərək laycığın müxtəlif vəziyyətlərdə yerləşməsi və təcridedici materialnın yerləşmə intervalları üçün sulaşdırma prosesinin modelləşdirilməsi həyata keçirilmişdir. Təcridetmənin optimal yerləşməsinin seçimi süzülmə həllərinin çox miqdarda resurs tələb edən riyazi modelləşdirilməsindən istifadə etmədən nəticələrin ehtimal olunan işlənməsindən istifadə etməklə aparılmışdır. Optimal təcridetmə üsulunun yüksək keçiricikli təbəqənin yerləşməsindən asılılığı nümayiş etdirilmişdir. Laycıq həndəsəsinin paylanma funksiyasının parametrləri ilə ümumiləşdirilmiş səmərəlilik göstəricisinin ehtimal hərəkəti arasında əlaqə qurulur. Modelləşdirmə özlülük nisbətinin müxtəlif göstəriciləri üçün aparımlşdır: Volqaboyu və Qərbi Sibir yataqları üçün bərabər özlülüklü və xarakterikdir.

Açar sözlər: neft layı; yüksək keçiricikli təbəqə; qeoloji qeyri-müəyyənlik; vaxtından əvvəl sulaşma; təcridetmə; stoxastik modelləşdirilmə; ikifazalı süzülmə; cərəyan borucuğu modeli.