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Hydrodynamic evaluation of the efficiency of flow deflecting technologies in conditions of formation of man-made filtration channels

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Abstract. The question is considered of the mechanism of waterproofing compounds at a late stage of development in zones of the formation that are different in geological heterogeneity. It is shown that man-made channels, which change the flow structure and distribution of mobile oil reserves, influence the process of filtration of injected water. The method of calculations is proposed, which allows to take into account the formation of channels and to determine their impact on the efficiency of flow deflecting technologies. To calculate the pressure, a hydroconductivity field is used at each point of the deposit, which is determined from the solution of the inverse coefficient problem.

Keywords: technogenic flood channels, water flooding cells, fixed flow tube method, short-term forecast, waterproofing composition, filtration flows, additional oil production, identification of hydraulic conductivity

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Despite the widespread introduction of flow-diverting technologies into the practice of oil production, the issue of the mechanism of their action in field conditions remains not fully understood. In many ways, this is agreed by the lack of methods for identifying and analyzing the most significant factors affecting the production of additional oil production. The article proposes a technological process based on the use of ready-made 3D geological and filtration models.

We also used data on geology, development, geological and technical measures and well testing (hydrodynamic studies of wells), stored as a database (Nasibulin et al., 2017). It was proposed to additionally build a model of the current energy states with identification of the hydraulic conductivity of the reservoir and the model of current tubes (Shelepov et al., 2017; Baushin et al., 2017), in which the possibility of working with man-made canals and blocking them with water insulating compounds was introduced.

The effectiveness analysis of the injection of water-insulating materials into the injection well, located in the center of the waterfloor element, allows us to obtain an uneven distribution of additional oil production in the producing wells. The distribution of additional production, as a rule, is as follows. About half of the wells show an increase in oil production. The remaining wells give a slight negative result. At the same time, there are always wells that do not respond to the application of technology. The effect was observed already the next month after the event and lasted for 4-6 months. The Koch principle 80/20 is evident, according to which only 20% of the wells provide an economic effect and make it possible to cover losses in neighboring wells. This character of the effect can be explained by the influence of technogenic processes associated with the injection of a large amount of water of different hydrochemical composition. As a result, the mineral components of the reservoir are leached out and the weakly cemented solid particles are mechanically removed. For example, in the Upper Jurassic polymictic reservoirs, taken for analysis, content of carbonate material on average ranged from 10-15%. The destruction of carbonate cement under the action of water injection at high pressure drops leads to the formation of tubular channels with high conductivity. The presence of super-reservoirs with a permeability of up to 10 D in the section further contributes to an increase in geological heterogeneity. During the development process, new channels are formed between injection and production wells, which coincide with the direction of the current tubes, which have minimum dimensions and maximum filtration rate. Fig. 1 shows an example of the change in the accumulated water-oil factor in

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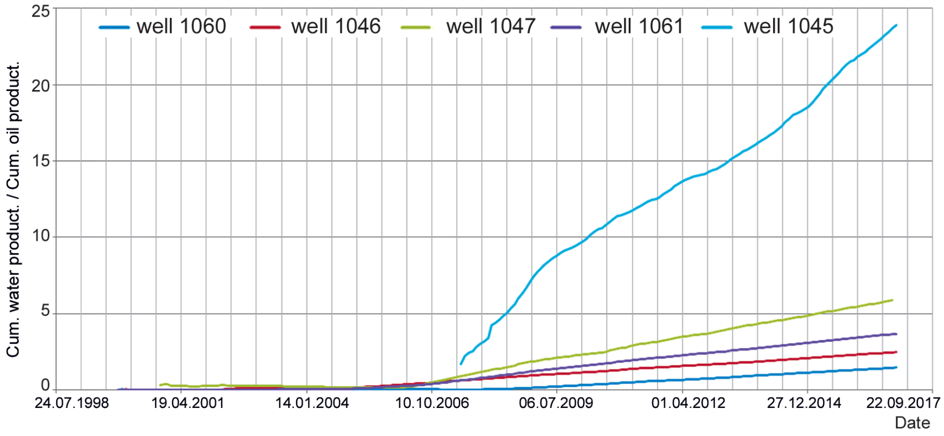

Fig. 1. The graph of the accumulated water-oil factor showing the well with the presence of technogenic filtration channel

one of the sections of the flooding, which includes five reacting wells. According to one of the wells, a sharp increase in water-oil factor is observed up to 24, while in the neighboring wells this ratio does not exceed 3-6.

A similar pattern of well irrigation can be traced in other areas, which indicates the presence of a wide network of technogenic filtration channels between injection and production wells.

The presence of water filtration channels is also noted for individual injection wells. So, according to well testing, more than 50% of the wells of the fields confined to polymict reservoirs, which are are characterized by radial filtration with the presence of cracks. The presence of the filter channel is also indicated by the fact that the current injectivity has increased several times relative to the initial one.

Using full-scale 3D models to evaluate the effectiveness of flow diverting technologies is of interest only from a mathematical point of view. They use permeability values on geophysical data with low accuracy. In addition, due to the peculiarities of the calculation methods, the radial nature of the movement of water from injection wells to production wells is manifested. Estimated reduction of watering from the injection of waterproofing materials, as a rule, is observed only after 2-2.5 years, which contradicts the practical results. Full-scale models do not take into account the fact of anthropogenic filtration channels and do not contain information about their position in the section opened by the well. 3D models do not contain an apparatus that allows blocking water-flushed canals by pumping waterproofing materials. Therefore, at a late stage of development, a new calculation method is required, which is focused on the current parameters of the formations that have undergone significant changes in the original properties, due to the huge volumes of injected water. Calculations show that when switching from a 3D full-scale model to an integrated grid for different upscaling options, the value of geological and mobile oil reserves is maintained, and the averaging error of geological reserves is within 2%. When switching to an integrated grid, the dynamics of development indicators also remain.

According to the accepted order of reception and examination of models, the three-dimensional model is used as a geological basis for hydrodynamic modeling. At the same time, it is required that it correspond to the calculation of reserves performed according to the current instructions of the State Reserves Committee for two-dimensional models. For this reason, for many deposits there is no need to use small 3D grids.

The energy regime of the deposit depends on the natural conditions and the water flooding system created and is “Engine” that defines the entire development process. For individual sites that are potential objects for the application of enhanced oil recovery methods, the energy regime determines the predominant direction of flow, flow through the boundaries of the sites, the activity of the outlined area and bottom water, and the nature of the interaction of wells.

When the pressure changes, the direction of the fluid movement changes. In addition, the energy mode also determines the nature of the interaction of the sampling zone with a gas cap. Therefore, great attention should be paid to identifying the relationship between sampling, reservoir pressure, the nature of the watering of individual wells and the presence of water outflow from the oil-bearing circuit. If the pressure rises, then the flow changes, the oil saturation changes. When analyzing the energy state of the reservoir, first of all, the flow rates, pressures and technical condition of the wells are linked. The calculation of the pressure field was carried out according to the equation of single-phase two-dimensional stationary filtration of a liquid, which can be written in the following form:

$$\nabla\left(\varepsilon\nabla p\right)=q\,, \tag{1}$$

where $\varepsilon = kh/\mu$ is the coefficient of hydraulic conductivity, k is the permeability, h is the thickness of the formation, μ is the viscosity of the fluid, p – pressure, q – intensity of sources and drain.

The boundary values in the outer region were set within the outer contour of oil-bearing, as well as with taking into account that the deposit boundary may be limited by the lines of tectonic disturbances, the internal contour of gas caps, lines of substitution or wedging of reservoirs.

If we consider the oil reservoir as a whole, then the energy regime of the site is not only one of the main characteristics of the development process, but also the determining factor for the efficiency of current-diverting technologies. In this regard, to coordinate the production parameters for a given date of calculation in the work (Bulygin et al., 2001) it was proposed to apply a calculation scheme with the identification of the reservoir hydroconductivity field.

Identification of the field of hydroconductivity. To restore pressure at each point of the reservoir we have to know the field of hydroconductivity. One of the ways to determine the field of hydraulic conductivity is to solve the inverse coefficient problem (identification problem).

Different methods for solving the problem of identifying reservoir parameters can be divided into explicit methods and implicit methods. In the following, the implicit identification method is considered (Elesin et al., 2018), when the estimate of unknown parameters is iteratively improved so that the pressure values obtained by solving the direct problem coincide with the known pressure measurements. In this case, a multiple solution of the direct problem with different values of the identified parameters is required. The essence of the method is to minimize the residual function J, which is the sum of squared differences between the measured pressure values $p^* = \{p_j^*\}_{j=1}^M$ characterizing the state of the reservoir, and the pressure values $p = \{p_j(K)\}_{j=1}^M$ calculated using a mathematical model:

$$J = J(K) = \frac{1}{2} r^T r,$$

where $K = \{\ln k_i\}_{i=1}^N$ logarithms of identifiable parameter values, $r = (p_1 - p_1^*, \ldots, p_M - p_M^*)^T$ is the residual vector, M is the number of pressure measurements, N is the number of identifiable parameters.

The minimization of the residual function is carried out by iterative methods, which are based on the construction of successive approximations of unknown parameters $K^{n+1} = K^n + \Delta K^n$, n = 1, 2, … such that $J(K^{n+1}) < J(K^n)$, where n is the iteration number, ΔK^n – increments of parameters. To stop an iterative process, two criteria are used:

1) Achievement of a given accuracy ε according to pressure measurements

$$\Delta p^m = \max_{j=1,M} \left| p_j(K^n) - p_j^* \right| < \varepsilon,$$

2) Slow convergence rate of the iteration process $J(K^n) - J(K^{n+1}) < 0.01 J(K^n)$ over 10 iterations.

Different algorithms for determining the increments of ΔK^n parameters lead to different minimization methods. These algorithms can be divided into three groups: direct search methods, gradient methods, various modifications of the Gauss-Newton method. In direct search algorithms, the minimization process is based only on the values of the function obtained for various values of the identified parameters.

As a rule, direct search methods have a low convergence rate and are rarely used in identification problems.

When constructing gradient methods at each iteration, it is necessary to calculate the derivatives of the function with respect to the desired parameters. Methods of steepest descent and conjugate gradients are widely used in identification problems. In the method steepest descent to build successive approximations of unknown parameters K^n, the gradient of the residual function is used:

$$g = \operatorname{grad} J(K) = \left\{ \frac{\partial J}{\partial K_i} \right\}_{i=1}^N,$$

(the sensitivity vector of the residual function relative to parameters). At each iteration, new parameter values are calculated using the formula:

$$K^{n+1} = K^n - \rho^n g^n,$$

where ρ^n is the step size determined from the minimum condition of the function $J_\rho(\rho^n) = J(K^n - \rho^n g^n)$. To find the minimum of the function J_ρ, various methods of one-dimensional minimization can be used.

The basis of various modifications of the Gauss – Newton method is the $H = AA^T$ approximation of the Hessian matrix of residual functions, where A is the sensitivity matrix:

$$A = \begin{pmatrix} \frac{\partial p_1}{\partial K_1} & \cdots & \frac{\partial p_M}{\partial K_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial p_1}{\partial K_N} & \cdots & \frac{\partial p_M}{\partial K_N} \end{pmatrix}$$

One of the modifications of the Gauss – Newton method, widely used in identification problems, is the Levenberg-Marquardt method. The vector of deviations in the Levenberg-Marquardt method approaches either the direction of the vector of the gradient of the residual function, or to the vector of deviations of the Gauss-Newton. The algorithm of the Levenberg-Marquardt method is written in the form:

$$K^{n+1} = K^n - (H + \mu^n E)^{-1} g, \quad \mu^{n+1} = \mu^n / 2,$$

where μ^n is the Marquardt parameter, E is the identity matrix. At each iteration, if the condition is violated:

$$J(K^n - (H + \mu^n E)^{-1} g) < J(K^n),$$

the μ^n coefficient is doubled until this condition is fulfilled. The initial value of the parameter m0 is taken an order of magnitude greater than the maximum singular number of the matrix H.

It is believed that the solution to the problem of identification is obtained if the specified accuracy of pressure measurements is achieved.

In terms of the numerical implementation of geological field data of real objects, the identification algorithm should take into account and preserve the heterogeneity of the hydroconductivity field, due to the presence of tectonic faults, wedging lines and reservoir replacement.

Analysis of the results of hydrodynamic calculations in conjunction with the study of the nature of the irrigation wells and the state of the energy regime of the reservoir sites showed the presence of channels between the injection and production wells. On open cells of the nine-point system, waterflooding located on the border with the external contour of oil-bearing capacity, channels can be formed that control the outflow of water outside the reservoir (Fig. 2).

In areas confined to the oil-water zone, having contact with plantar and contour waters, the nature of fluid movement may be significantly different than in the central part of the reservoir.

A part of the waterflooding cells adjacent to the oil-bearing contour, at low sampling compensation values, injection is characterized by the inflow of formation mineralized water due to the external oil-bearing contour. Under these conditions, the formation of channels of filtration does not occur. Another part of the flooding cells is characterized by the outflow of pumped water out of the oil-bearing circuit. The significant role of the filtration channels in the process of oil displacement is indicated by a steady increase in conductivity and permeability, which is not accompanied by an increase in the current reservoir pressure.

Conducting short-term forecasts based on flow tubes with fixed boundaries. Separate tubes of flow separated by lines of the lowest filtration rates emanating from the injection well form drainage sectors (so-called lobes). Each sector is characterized by the constancy of the law of conservation. This means that the reservoir parameters and fluid flow characteristics for each segment are unchanged for a time equal to 1-2 years, that is, from the beginning of the comparison base and several months after the effect ends. This time period is quite enough for the calculation of the basic variant and the variant with the use of flow-diverting technologies. A sectoral model using flow tubes, obtained from a 3D full-scale model, by transferring it to a 2D model of the flow state and the model of flow tubes can be used to calculate the design of the helium shield setting. The initial oil saturation values in flow tubes are determined by solving a full-scale problem for the current date. Next, the problem of two-phase filtration in flow tubes is solved with the calculation of the predominant movement of water through current tubes with high conductivity. Calculations are carried out taking into account approximately 500 flow tubes. The distribution of the current oil saturation in modeling the extrusion fronts and channels of high permeability is shown in Fig. 3. As channels of different widths, washed as a result of water injection into the injection well, for each drainage area, flow tubes of minimal length were taken (Fig. 3a).

The proposed filtering model allows us displaying a complex flow of fluid in the form of a combination of displacement fronts and water breakthroughs through the filtration channels (Fig. 3b). The presence of water supply channels is indicated by a sharp increase in the

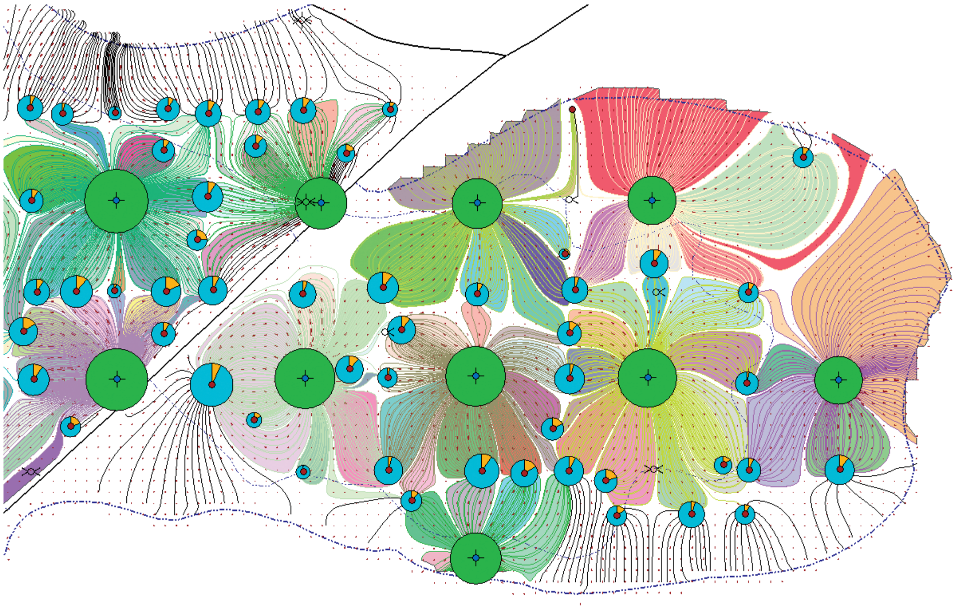

Fig. 2. Nine-point water-flooding cells with allocated drainage sectors

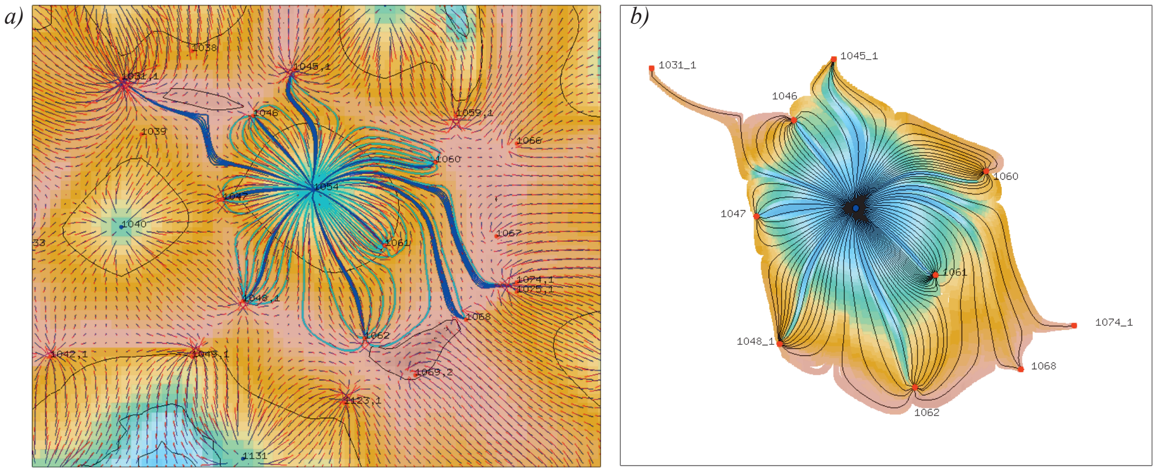

Fig. 3. Channel configuration (a) and saturation distribution (b) taking into account the channels

current injectivity of injection wells relative to the initial one, as well as the presence of production wells with high water withdrawals. The tubes are differentiated in length and width. It is possible to simulate different volumes of injection of a water insulating system, which will move mainly through wide channels (Fig. 4).

Through narrow channels with low permeability helium system will not go at all. The calculations should take into account that only part of the drainage sectors will be characterized by the presence of breakthrough filtering channels. Figure 5 shows the characteristic increase in additional oil production for the drainage sector, where the channels were isolated using injection of flow-diverting materials (Fig. 5), in which cross-linked polymer systems were used in the conditions of the late stage of development of a real field, where tens and hundreds of tons of oil were selected from wells, the deviation from the actual oil production curve calculated by the proposed method, the effects will be less significant (Fig. 6). At the same time, in the surrounding wells, where there are no technogenic channels for

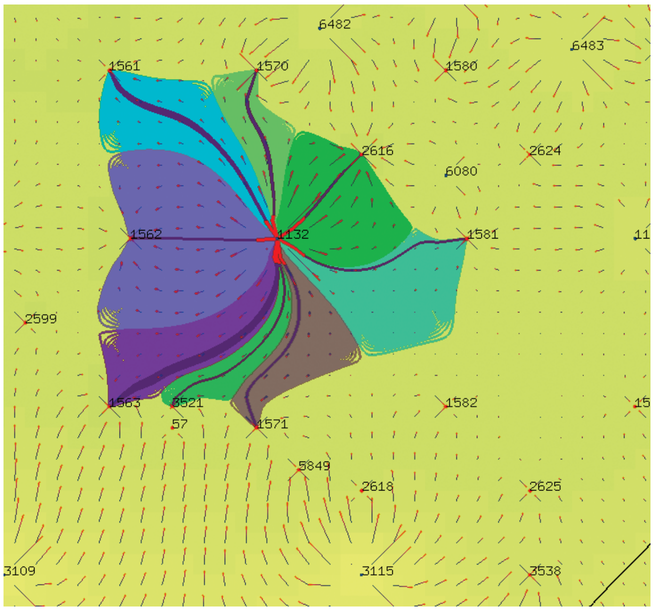

Fig. 4. Channels of different thickness washed in flow tubes of minimum length and injection of water insulating composition

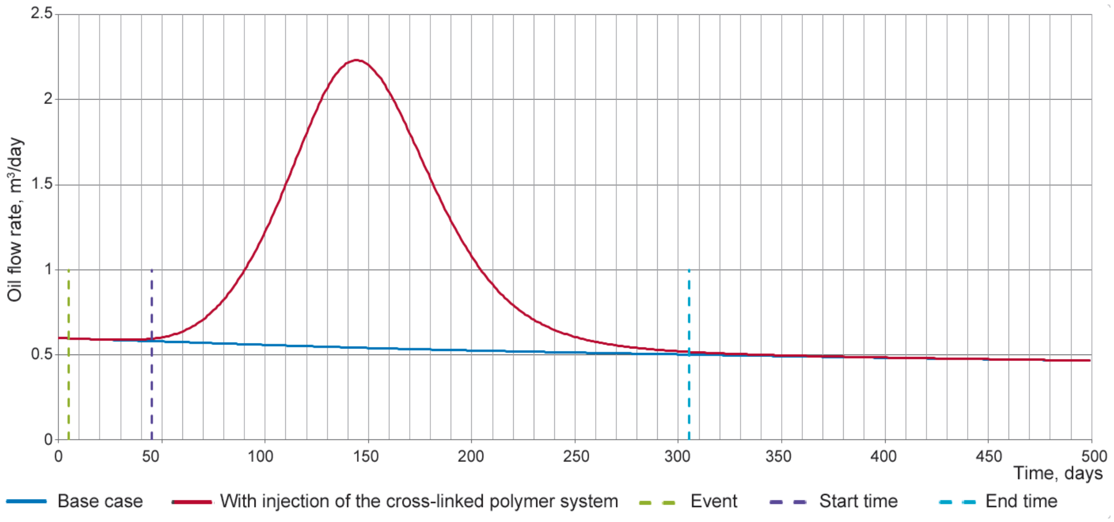

Fig. 5. The prediction of the flow rate of oil obtained from blocking the channel filtration. The blue line in fig. 5 shows the base case. The increase in oil production from injection of the cross-linked polymer system into the injection well is shown by a red line. Dashed lines indicate the time of the event (green), the start time (purple) and the end time (blue) of the resulting effect

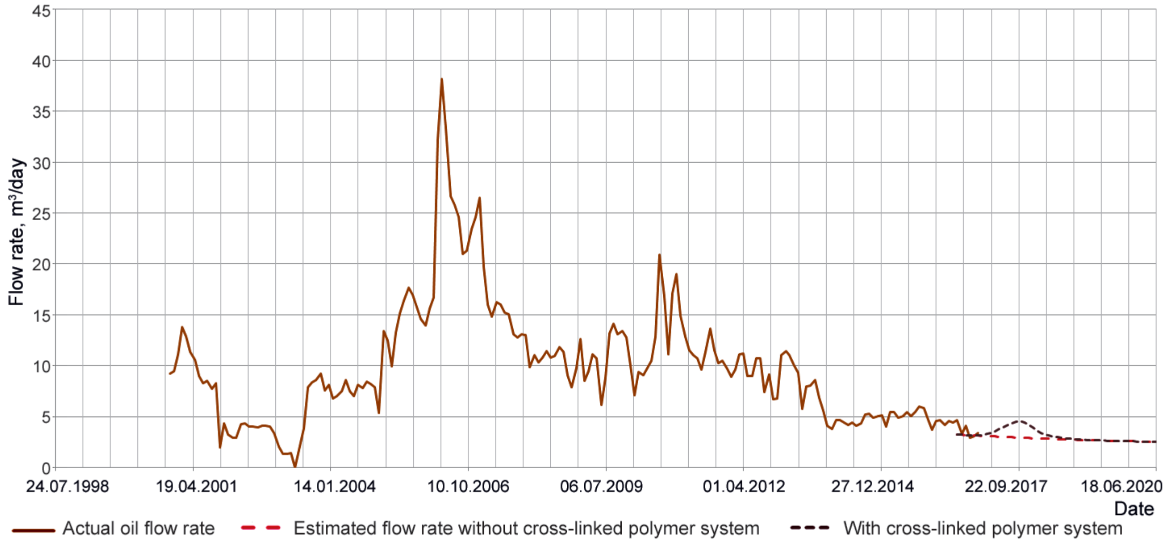

Fig. 6. Dynamics of oil production in modeling the injection of an insulating system

filtering, there will be no reaction to the injection of the water isolating system. The question about the features of the manifestation of the mechanism of action of water insulating compositions in various areas of heterogeneity and depletion of water-flooding reservoir is unexplored. Its solution is extremely important for determining the structural-mechanical properties and volume of injection of water insulating compositions that determine the resistance to erosion of helium screens. We should not forget about the strong influence on the formation of channels of geological features reservoir structure, which was not considered in detail in this work.

Conclusions

1. Maps of permeability, hydraulic conductivity, isobars, filtration rates, obtained from hydrodynamic calculations, in combination with the study of the character of well watering and the energy state of the deposits, can be used to diagnose the presence of filtration channels.

2. Technogenic channels significantly change the structure of filtration flows and the distribution of mobile oil reserves within individual sections of deposits, which affects the efficiency of current-diverting technologies.

3. A calculation method is proposed to avoid common mistakes associated with limiting the duration of the effect in time and the localization of the effect in the area of the injection and the first row of the producing wells surrounding it.

References

Baushin V.V., Bulygin D.V., Nikolaev A.N. (2017). Present State Reservoir Model – Basis of Smart Field. *Neft'.Gaz.Novatsii = Oil.Gas. Innovations*, 9, pp. 44-47. (In Russ.)

Bulygin D.V., Medvedev N.Ya., Kipot' V.L. (2001). Modeling of the geological structure and development of oil deposits in the Surgut arch. Kazan: «DAS» Publ., 191 p. (In Russ.)

Elesin A.V., Kadyrova A.Sh., Nikiforov A.I. (2018). Definition of the reservoir permeability field according to pressure measurements on wells with the use of spline function. *Georesursy = Georesources*, 20(2), pp. 102-107. DOI: https://doi.org/10.18599/grs.2018.2.102-107

Nasibulin V.G, Bulygin D.V., Komarova O.V., Baushin V.V., Shelepov V.V., Ramazanov R.G. Certificate of computer program registration No. 2017610455. 11/01/2017. ArtGeoBase, version 1.0. Loading and maintaining a database of geological and hydrodynamic models.

Shelepov V.V., Bulygin D.V., Ramazanov R.G., Baushin V.V. (2017). Computer models for the analysis of stimulation methods effectiveness. Moscow: «KDU», «Universitetskaya kniga», 232 p. (In Russ.)

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