ISSN 2712-8008
Volume / Том 25 №2 2025
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622.276.6
Article / Статья


## Multivariate modeling of injection well perforation systems

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## Многовариантное моделирование систем перфорации нагнетательного фонда

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Received / Получена: 16.12.2024. Accepted / Принята: 05.12.2024. Published / Опубликована: 01.04.2025

*Keywords:*
waterflooding system, reservoir pressure maintenance, optimization of the reservoir pressure maintenance system, high heterogeneity, uneven impact of injection, increasing development efficiency, injection redistribution, alignment of the injectivity profile, multivariate hydrodynamic modeling, geological and technical measures, impact of injection wells, displacement process, flooding source, breakthrough of the injected agent, hydrodynamic connection.

The Upper Visean-Bashkirian oil and gas complex makes a significant contribution to the volume of oil production in the Perm Krai. The development objects of the oil and gas complex are characterized by a complex geological structure with high heterogeneity of the formations. At most of the production objects, a decrease in reservoir pressure was noted in the zones of selection of production wells, which was due to the insufficient influence of the applied flooding systems to maintain it. One of the factors that has a negative impact on the efficiency of the flooding system is the uneven influence of injection wells on production wells in the conditions of development of a highly dissected formation. When developing production objects with a large operating stock of production and injection wells, the task is to find the most optimal scheme of the injection wells influence on production wells. High variability of possible combinations of perforation intervals due to significant dissection and inconsistency of the reservoir layers distribution over the area significantly complicates the solution of this problem.
The authors propose an approach to optimization of the reservoir pressure maintenance system based on multivariate calculations using a permanent geological and hydrodynamic model. The essence of the approach lies in comparing multiple scenarios for redistributing the injected agent across the section by enumerating options with different perforation intervals in the injection wells. The recommended option is selected based on a combination of two factors: maximizing oil production and restoring or stabilizing reservoir pressure in the deposit. Using the proposed approach, complex geological and technical measures were formed in the injection wells. They included isolation of injection intervals that may potentially experience a water breakthrough, or intervals that did not affect production wells, as well as completion of unperforated reservoir intervals. The use of the proposed approach improves the efficiency of the current reservoir pressure maintenance system by increasing reservoir pressure, involving new intervals in the process of displacing injected water, and reducing the risk of a water breakthrough.

*Ключевые слова:*
система заводнения, поддержание пластового давления, оптимизация системы ППД, высокая неоднородность, неравномерное влияние закачки, повышение эффективности разработки, перераспределение закачки, выравнивание профиля приемистости, многовариантное гидродинамическое моделирование, геолого-технические мероприятия, влияние нагнетательных скважин, процесс вытеснения, очаг заводнения, прорыв закачиваемого агента, гидродинамическая связь.

Верхневизейско-башкирский нефтегазоносный комплекс вносит значительный вклад в объем добычи нефти в Пермском крае. Объекты разработки рассматриваемого нефтегазоносного комплекса характеризуются сложным геологическим строением с высокой неоднородностью пластов. На большинстве рассматриваемых эксплуатационных объектов отмечается снижение пластового давления в зонах отбора добывающих скважин, что обусловлено недостаточным влиянием применяемых систем заводнения для его поддержания. Одним из факторов, оказывающих негативное влияние на эффективность системы заводнения, является неравномерное влияние нагнетательных скважин на добывающие в условиях разработки высокорасчлененного пласта. При разработке эксплуатационных объектов большим действующим фондом добывающих и нагнетательных скважин стоит задача поиска наиболее оптимальной схемы влияния нагнетательных скважин на добывающие. Высокая вариативность возможных сочетаний интервалов перфорации из-за значительной расчлененности и невыдержанности распространения пропластков коллекторов по площади существенно осложняет решение этой задачи.
Авторами предложен подход к оптимизации системы поддержания пластового давления на основе многовариантных расчетов с использованием постоянно действующей геолого-гидродинамической модели. Суть подхода заключается в сравнении множества сценариев перераспределения закачиваемого агента по разрезу путем перебора вариантов с различными интервалами перфорации на нагнетательном фонде. Выбор рекомендуемого варианта реализуется на основе сочетания двух факторов – максимизации добычи нефти и восстановлении либо стабилизации пластового давления по залежи. С помощью предлагаемого подхода сформированы комплексные геолого-технические мероприятия на нагнетательном фонде. Они включают в себя изоляцию интервалов закачки, по которым потенциально может быть прорыв воды, либо интервалов, не оказывающих влияние на добывающие скважины, а также дострел неохваченных перфорацией интервалов пласта. Применение предлагаемого подхода позволяет повысить эффективность текущей системы поддержания пластового давления за счет увеличения пластового давления, вовлечения в процесс вытеснения закачиваемой водой новых интервалов и снижения риска прорыва воды.

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Please cite this article in English as:
Raspopov A.V., Filatov M.A., Krivonos S.V., Timofeev O.V., Bartov D.O. Multivariate modeling of injection well perforation systems. *Perm Journal of Petroleum and Mining Engineering*, 2025, vol.25, no.2, pp. 102-108. DOI: 10.15593/2712-8008/2025.2.6

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Многовариантное моделирование систем перфорации нагнетательного фонда/ А.В. Распопов, М.А. Филатов, С.В. Кривонос, О.В. Тимофеев, Д.О. Бартов // Недропользование. – 2025. – Т.25, №2. – С. 102–108. DOI: 10.15593/2712-8008/2025.2.6

## Introduction

The most common method of hydrocarbon field development is reservoir pressure maintenance by water injection into the reservoir. Despite the enormous experience of application, the theory and practice of this method are constantly improving [1–4]. The diversity of geological and physical conditions in different oil and gas bearing regions of the world, the need to develop objects with increasingly complex geological structure and lower productivity stimulate the continuous development of reservoir pressure maintenance methods [5–7].

In the modern period of oil production in Perm Krai, one of the main oil and gas bearing complexes (OGC) is the Upper Visei-Bashkirian one [8, 9] which accounts for a quarter of all oil produced in Perm Krai and 20 % of the annual production at the moment. At the same time, 25 % of residual oil reserves in Perm Krai are concentrated in this OGC. The reservoirs are predominantly medium-permeable limestones saturated with oil of both low and high viscosity. The productive sediments are characterised by significant heterogeneity of the geological structure with high values of compartmentalization.

In the Upper Visei-Bashkirian OGC the reservoir pressure maintenance (RPM) system is organised at 42 of the 64 production facilities (PF). At the same time, the majority of PFs (83 %) use an intra-contour flooding system, while the remaining (17 %) use a near-contour flooding system. More than half of the PFs have zones of low reservoir pressure, what indicates insufficient impact of injection wells.

The analysis of the energy state and the dynamics of technological indicators revealed an insufficient efficiency of the waterflood system with compensation for the waterflood system of about 100 %. Besides, intensive breakthrough of injected water is observed when the volume of agent injection increases.

Improvement of reservoir pressure maintenance systems at the development sites of the Upper Visei-Bashkirian complex will increase its efficiency. This increase can be comparable, and in some cases even exceed the efficiency of expensive tertiary enhanced oil recovery (EOR) methods [10–13].

## Improving the Efficiency of the RPM System

Analysis of the works of specialists who studied the efficiency of RPM systems has revealed a number of the most typical negative factors affecting the reduction of its efficiency, except for the losses of surface and technical working agent in the well: the outflow of injected water into the contour area from the contour and near-contour injection wells; the organisation of reservoir pressure maintenance in low-productive formations with complex geological structure after a significant decrease in the initial reservoir pressure; incomplete impact of injection wells on the operation ones due to the heterogeneity of the lithological structure of productive deposits; random distribution of agent injection over the area of the productive formation [14–17].

Due to the high compartmentalization and heterogeneity of the section of the PFs under consideration inefficient injection volumes are identified due to the discrepancy between the perforation intervals of injection and production wells. At the same time, a complete comparison of intervals does not guarantee the efficiency of the reservoir pressure maintenance system since this can lead to water breakthroughs through highly permeable channels [18].

It is difficult to trace such channels due to the dissected and highly differentiated by filtration-capacity properties section in conditions of high variability of interval comparison with a large number of active wells. In general, if at the initial stages of field development the main focus is on reservoir pressure maintenance, at later stages the main objective of optimising the RPM system is the reduction of water cut and injection without loss of oil production [1]. At the same time, the introduction of the analysis method which consists in preliminary modelling of the situation, identification of possible problems and reaction to them, allows preventing possible oil losses in advance [16]. Multivariate calculations on the hydrodynamic model allow us to identify the optimal waterflooding system and, consequently, to determine the parameters of waterflooding systems, both leading to oil losses and increasing its recovery. At present, multivariate hydrodynamic modelling has proved itself in assessing uncertainties in parameters affecting production levels [19–21].

Multivariate calculations on the hydrodynamic model are preceded by the stage of analysis of the applied waterflooding system. The analysis focuses on the separation of non-productive injection and assessment of hydrodynamic connectivity between injection and production wells [15, 21, 22]. The following types of methods are used to find hydrodynamic connectivity between wells: technological methods, such as tracer injection and interference testing [23–27]; analytical methods, which consist of processing and analysing field data using various mathematical and numerical methods. [28–31]. Such methods are based, among others, on hydrodynamic modelling of different levels of complexity [32–34]. At the moment, development engineers use a wide variety of analytical methods to assess the mutual influence between wells, starting with the simplest statistical methods, such as the Spearman and Kendall rank correlation methods [35–37]; they are used mainly for rapid assessment. There are also the most resource-intensive methods, such as hydrodynamic modelling and neural networks [28, 38].

Non-productive injection means not only inefficient injection which does not perform useful work in the productive reservoir, but also the volume of water that did not reach the wellheads of injection wells due to the failure of the surface RPM system, and the volume of water that did not reach the target facility due to technical reasons – violations of the well structure [39]. In order to identify non-productive injection development engineers usually use the hydrodynamic modelling tool, but at the same time, for operational evaluation analysis, many methods are used to assess the efficiency of injection based on the material balance equation [14].

To solve the problem of RPM system optimization in the conditions of developing highly dissected and highly heterogeneous PF such as Upper Visei-Bashkirian OGC of Perm Krai the authors used multivariate calculations with the application of constantly operating geological and hydrodynamic model. The essence of the approach is to compare multiple scenarios of redistribution of injected agent across the section by selecting variants with different perforation intervals in the injection well stock [40]. As a result, on the basis of calculations, a set of geological and technical measures (GTM) is selected at the injection stock, including repair and insulation works

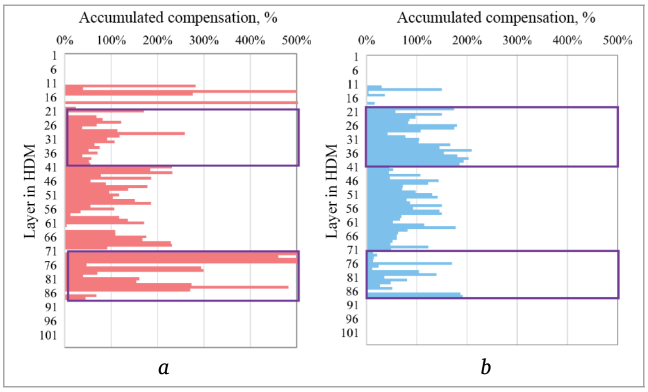


Fig. 1. Comparison by accumulated compensation:
*a* – basic variant; *b* – recommended variant

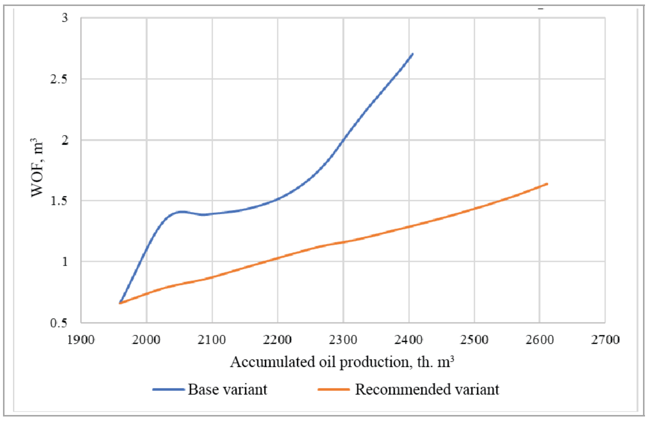


Fig. 2. Dependence of WOF on cumulative oil production

of injection intervals that do not affect the producing wells as well as having a probability of water breakthrough, and completion of reservoir intervals not covered by perforation to increase the influence on the extraction zones [41–43].

Compared to the traditional method, in which the determination of optimal perforation intervals consists of sequential selection and calculation of each GTM on the HDM, the proposed approach allows not only to speed up the process of selecting measures on the injection reservoir, but also to cover a greater number of alternative scenarios for optimising the RPM system.

Approbation of the approach was carried out on the PF C2b (Bsh) of one of the fields of Perm Krai. More than 300 variants of calculations were carried out. The variants differed from each other by perforation intervals for all injection wells. Within the framework of the calculations, the parameter of "reservoir – well" connectivity was varied for each injection well in the range from 0 to 1. This parameter is taken as an uncertainty indicator. A total of 150 modifications were incorporated into the model for 15 injection wells. On average, about 10 parameters of connectivity were varied for each well (0 or 1) by perforation interval. The forecast period was 10 years [40].

Such characteristics as the increase in cumulative oil production, stabilisation or increase in reservoir pressure were chosen as target functions [43–46]. When analysing various options it was chosen the recommended one which provides maximum oil production for 10 years, contributes to stabilisation of reservoir pressure in the field and minimises water flooding of production wells.

In the recommended variant it was possible to ensure equalisation of injection along the section, which is confirmed by the distribution of accumulated compensation by layers of the hydrodynamic model in comparison with the basic variant (Fig. 1, *a*, *b*). When analysing the distribution of accumulated compensation, redistribution of injection from the bottom part to the roof and middle part of the formation is noted. At the same time, in the basic variant (with actual perforation intervals in injection wells), the accumulated compensation reaches high values in some layers; in the recommended variant, the accumulated compensation is equalised at the average level of 100–120 %. By redistributing injection in the reservoir section, the risk of premature water breakthrough into production wells was reduced.

The recommended option compared to the base case is characterized by a lower rate of well water flooding and high cumulative production (Fig. 2), which is caused by more optimal penetration and coverage by injection along the reservoir section.

Intervals for which there is a possibility of water breakthrough are isolated in the recommended version; the dependence has the form of a straight line and is characterized by uniform displacement. Cumulative oil production for the recommended case was 2611 thousand $m^3$, water-oil factor (WOR) at the end of the calculation – 1.64 $m^3/m^3$; Base Case – 2406 thousand m3, WOR – 2.7 $m^3/m^3$. The increase in oil production was 8.5 % with a decrease in WOR by 39 %.

Also, in the recommended option it has been noted a change in the penetrated layers for injection wells by 24.5 % compared to the base option, which includes insulation and re-perforation of layers in the ratio of 30/70 %. It is enough to isolate 30 % of the opened interlayers in order to get almost half as much water. To obtain 8.5 % of additional oil production, it was necessary to open more than twice as many additional layers. At the same time, it should be mentioned that additional perforation was carried out on the layers of the top part of the formation, where there are more penetrated layers in the production well stock compared to the injection one (Fig. 3).

In addition, the middle part of the reservoir (layers 40–42) was isolated as far as production and injection wells connectivity was clearly broken (Fig. 4).

## Analysis of Multivariant Calculation Results

According to the results of the analysis of the performed calculation variants, it was found that in 26 % of variants there is an increase in the weighted average reservoir pressure compared to the base variant, in 27 % of variants the reservoir pressure does not change, and in half of variants the reservoir pressure is lower than in the base variant.

To determine the amount of unproductive injection, the authors determined the probable share of influence of injection wells on production wells using the tracer function and drainage matrix in the hydrodynamic model. Thus, the entire volume of injected water is divided into effective and ineffective water, which in turn is divided into injected water escaping into the lenses and out of the loop, as well as water entering previously watered perforation intervals and high-permeability channels leading to premature watering of production wells.

In comparison of different options (Fig. 5), the lowest volume of effective injection (18 %) is observed in the option with maximum penetration since the intervals leading to premature intensive watering of production wells are involved. The recommended variant with the highest oil production, relative to other variants, is characterised by a smaller opening of watering intervals and a higher percentage of effective injection.

To analyse the influence of the injection well perforation system on the energy state of the PF, the variants were ranked according to the dynamics of the average reservoir pressure of the deposit. The obtained variants were differentiated by efficiency groups into positive, negative and neutral. Positive variants were taken as calculation variants for which the average reservoir pressure in the deposit is 1 MPa or more higher than the reservoir pressure of the base variant. Neutral variants are those for which the reservoir pressure changed by no more than 1 MPa. Negative variants showed a decrease in formation pressure by more than 1 MPa.

To analyse the effect of changing the perforation pattern of injection wells on the performance of surrounding production wells, the options are grouped separately for each injection well kitchen (table):

– with a greater impact of perforation change, where both reservoir pressure and additional oil production increased compared to the base case;

– with partial impact from perforation change (increase in oil production without affecting reservoir pressure);

– with the smallest impact from perforation change or no impact at all (increase in reservoir pressure with no impact on oil production).

The greatest impact from the change in perforation in injection wells is observed in the kitchen in the dome part of the reservoir, which is characterized by higher oil-saturated thicknesses and better reservoir properties. The zones with the least impact are located in the marginal part of the reservoir, mainly in the eastern part, the wells of which are located in lower thicknesses and worse reservoir porosity and permeability, as well as with higher stratification of the reservoir in the interwell space.

Analyses of production and injection wells connectivity were carried out for the base and recommended variants. In the recommended variant the number of producing wells where previously the injection stock had insufficient influence increased, their number was about 16 %. The main growth of oil production is caused by two reasons: complete redistribution of pumping in completion wells (closing of current intervals, perforation of new ones); new distribution of injectivity profile due to additional perforation of other intervals.

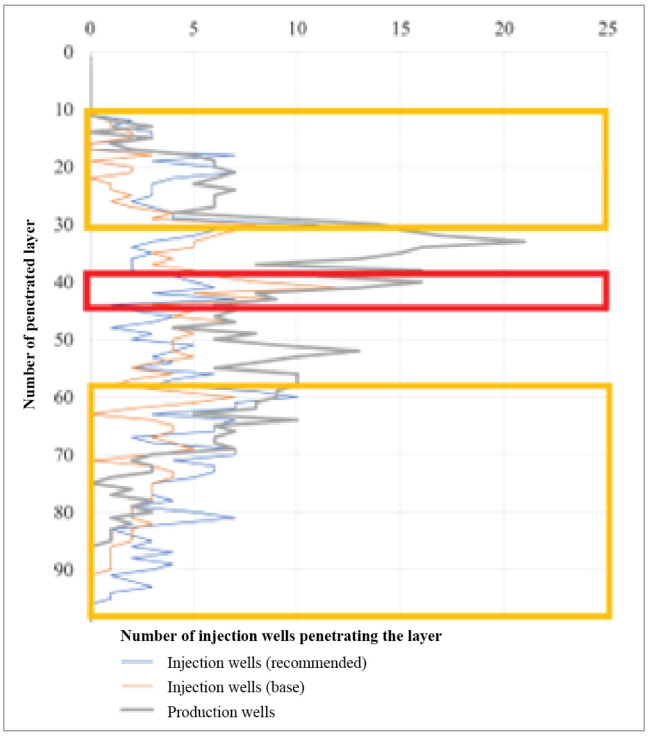


Fig. 3. Distribution of the number of wells, penetrating layers

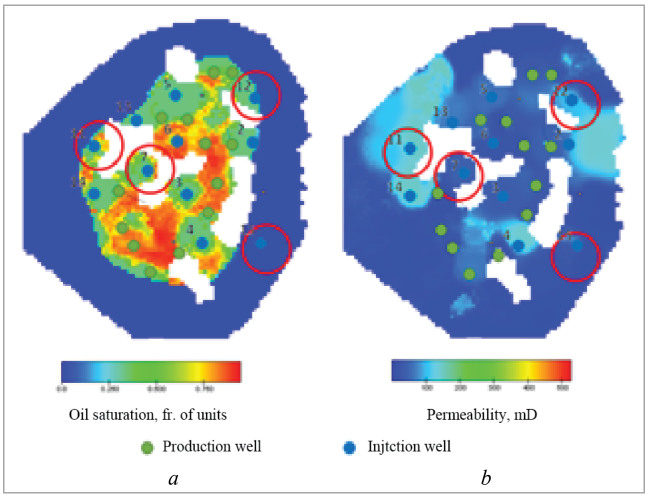


Fig. 4. Example of the Distribution of the Current Oil Saturation (*a*) and Permeability (*b*) Cube in 41 Layers of the Model with Identification of Wells with Producing Well Stock Connectivity

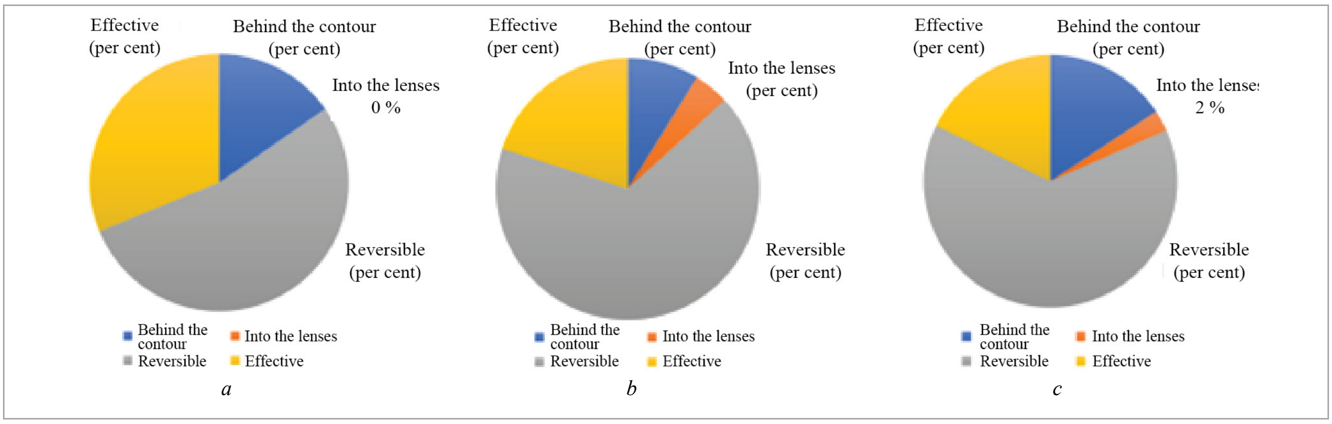


Fig. 5. Percentage distribution of injection of the compared variants: *a* – recommended variant; *b* – base variant; *c* – variant with maximum penetration

Distribution of the ensemble of variants by watercut centres

| Element number | Positive options by pressure, % | Positive options on additional oil production, % | Positive options by pressure and additional oil production |
|---|---|---|---|
| 1 | 2.7 | 95.3 | 2.7 |
| 2 | 1.7 | 100.0 | 1.7 |
| 3 | 45.2 | 58.8 | 23.9 |
| 4 | 32.6 | 39.5 | 8.6 |
| 5 | 5.3 | 99.7 | 5.3 |
| 6 | 29.6 | 99.7 | 29.6 |
| 7 | 23.9 | 100.0 | 23.9 |
| 8 | 45.5 | 92.0 | 42.5 |
| 9 | 33.6 | 95.3 | 31.9 |
| 10 | 2.7 | 6.3 | 0.0 |
| 11 | 4.3 | 93.7 | 4.0 |
| 12 | 1.0 | 100.0 | 1.0 |
| 13 | 22.9 | 98.0 | 21.3 |
| 14 | 15.9 | 78.7 | 15.0 |
| 15 | 26.2 | 100.0 | 26.2 |

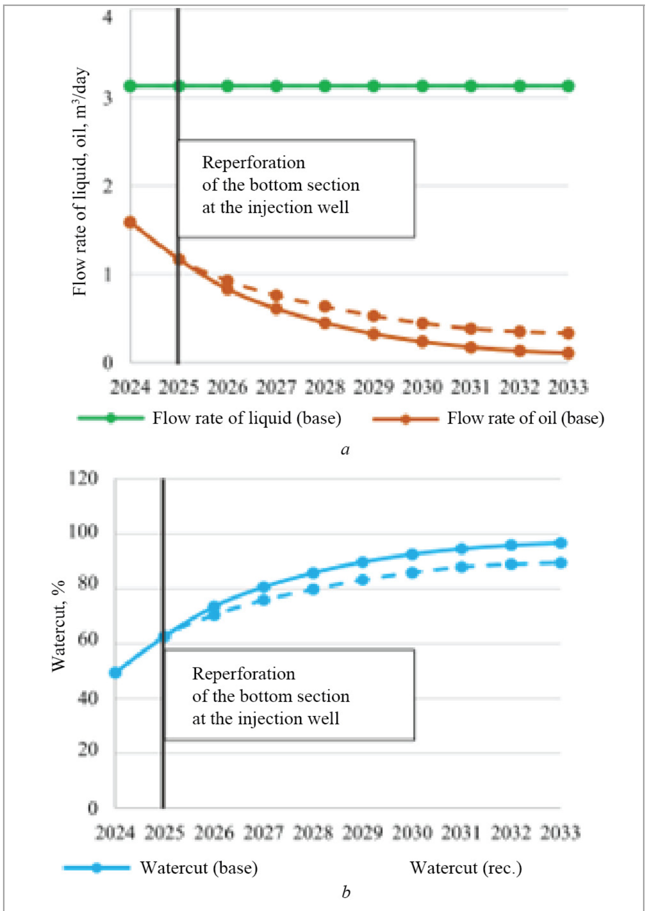


Fig. 6. Dynamics of production well operation:
*a* – liquid and oil flow rate, m$^3$/day; *b* – water flooding, %

A complete change in the configuration of perforation intervals at single injection wells relative to the base case is noted on wells located behind the contour, where there is a low connectivity with nearby production wells.

For example, for the area of the well located in the north-eastern part of the deposit according to the results of calculations it is recommend the penetration into the roof part of the formation which is more productive in terms of its characteristics compared to the middle part recommended for isolation. Such redistribution of injection makes if possible to increase the efficiency of injection impact on the producing reservoir and reduce the amount of injection going beyond the contour.

According to the results of multivariant modeling in the area of the well located in the eastern part of the reservoir it is recommended to perforate the bottom part of the formation. Such operation makes possible to redistribute injection so that a smaller volume of injection agent falls into relatively highly permeable channels connecting the injection well with one of the surrounding production wells. Calculations show that as a result of the redistribution of the injected water flow the watercut of the production well decreased by 10 % in the last of calculations compared to the baseline scenario (Fig. 6).

Analysis of each kitchen separately showed that there is a potential to increase the efficiency of the implemented development system by changing the perforation scheme of injected wells.

## Conclusion

High heterogeneity of the reservoir of the Bashkir sediments complicates the processes of oil displacement by injected water and maintenance of the reservoir pressure owing to the violation of reservoirs connectivity both vertically and horizontally. Under these conditions the achieved water flooding coverage can be increased by optimizing the perforation system of the injected wells.

The authors used the method of multivariate calculation on the hydrodynamic model. The application of the proposed approach makes it possible to speed up the process of selecting measures for the injection fund at the expense of automatic enumeration of injection well perforation intervals and cover more alternative options.

In the process of analysis of the recommended variant it was concluded that in the application of multivariate modeling approach it was possible to involve new reservoir intervals in the displacement process, reduce the risk of water breakthrough by isolating highly permeable intervals, and increase the volume of effective injection.

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Funding. The research had no sponsorship.
Conflict of interest. The authors decalare no conflict of interest.
The authors' contriburion is equivalent.