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Efficiency of Stationary and Non-Stationary Modes of Hot Water Injection during the Development of High-Viscosity Oil Deposits in Carbonate Reservoirs of the Komi Republic Field

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Эффективность стационарного и нестационарного режимов закачки горячей воды при разработке залежи высоковязкой нефти в карбонатных коллекторах месторождения Республики Коми

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highly-viscous oil, advance watering, matrix, fractures, thermal methods, hot water, produced water, displacement characteristics, geological and technological model, stationary injection, cyclic injection, piezoconductivity, half-cycle, chemical composition, unprofitable wells, hydraulic transport.

The paper presents a geological and field analysis of the effectiveness of stationary and non-stationary operating modes of the reservoir pressure maintenance system, during which hot water was pumped during the development of one of the carbonate deposits of the Timan-Pechora oil and gas province. The determining factors for the complexity of the development of the studied object are the ultra-high viscosity of oil and significant geological heterogeneity. Due to these factors, advanced watering complicates the development of the deposit. The current oil-water factor is 7.9. Increasing the efficiency of development of the facility is possible, among other things, by improving the technology of hot water injection, organized at the pilot site of the deposit in 2020.
Based on the negative experience of implementing the technology associated with water breakthroughs to production wells during stationary injection, a complex injection technology was developed. It based on a combination of cyclic hot water injection, chemical composition use in injection wells to equalize the displacement front and prevent water breakthroughs in producing wells, and limiting the produced water volume to reduce unproductive injection and reduce the water-oil factor by shutting down unprofitable high-rate wells.
Non-stationary flooding improves the efficiency of reserves recovery due to the initiation of fluid exchange between pore blocks and fractures due to the created variable pressure gradient, while stationary injection allows only the most permeable intervals to be involved in oil reserves. In conditions of high water cut, optimization of the injection technology will increase the recovery rate of residual oil reserves and reduce produced water volume, as well as ensure greater economic efficiency of reservoir development by reducing operating costs.

Ключевые слова:
сверхвязкая нефть, опережающее обводнение, матрица, трещины, тепловые методы, горячая вода, попутно добываемая вода, характеристики вытеснения, геолого-технологическая модель, стационарная закачка, циклическая закачка, пьезопроводность, полупериод, химическая композиция, нерентабельные скважины, гидротранспорт.

Представлен геолого-промысловый анализ эффективности стационарного и нестационарного режимов работы системы поддержания пластового давления, при которых проводилась закачка горячей воды при разработке одной из карбонатных залежей месторождения Тимано-Печорской нефтегазоносной провинции. Определяющими сложность разработки исследуемого объекта являются сверхвысокая вязкость нефти и значительная геологическая неоднородность. Вследствие указанных факторов разработка залежи осложнена опережающим обводнением. Текущий водонефтяной фактор составляет 7,9. Повышение эффективности разработки объекта возможно в том числе за счет совершенствования технологии закачки горячей воды, организованной на опытном участке залежи в 2020 г.
Авторами статьи на основе негативного опыта реализации технологии, связанного с прорывами воды к добывающим скважинам в период стационарной закачки, разработана комплексная технология закачки, которая основана на сочетании циклической закачки горячей воды, применения химической композиции в нагнетательных скважинах для выравнивания фронта вытеснения и предупреждения прорывов воды в добывающие скважины, и ограничения объемов попутно добываемой воды для сокращения непроизводительной закачки и снижения водонефтяного фактора за счет остановки нерентабельных высокодебитных скважин.
Нестационарное заводнение позволяет улучшить эффективность извлечения запасов благодаря инициации обмена флюидами между поровыми блоками и трещинами за счет создаваемого переменного градиента давления, тогда как стационарная закачка позволяет вовлечь запасы нефти только наиболее проницаемых интервалов. В условиях высокой обводненности продукции оптимизация технологии закачки позволит повысить темп отбора остаточных запасов нефти и снизить объемы попутно добываемой воды, а также обеспечить большую экономическую эффективность разработки залежи за счет снижения операционных расходов.

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Introduction

The modern trend of changes in the structure of current oil reserves determines the increasing relevance of the search for the most effective technologies for the development of deposits with ultrahigh fluid viscosity.

In the article it is considered the experience of implementing stationary and non-stationary modes of hot water injection during the development of one of the carbonate deposits in the Timan-Pechora oil and gas province. This province is characterised by ultra-viscous oil and significant geological heterogeneity, therefore the development of the deposit is complicated by the need to extract a large volume of associated water. Effectivization of field producrion could be possible, among other things, by improving the technology of hot water injection, which was organised at the pilot section of the deposit in 2020.

In conditions of high water cut, optimisation of the injection technology will increase the rate of extraction of residual oil reserves, reduce the volume of produced water and operating costs.

Brief Geological and Physical Characteristics of the Productive Formation

The carbonate deposit of the reservoir-massive type with an oil-bearing floor of up to 300 m is characterised by a complex geological structure. Productive sediments lie at an average depth of -1200 metres. The fracture-pore-cavernous type reservoir has high dissection of 51.1 units, permeability on average of 0.857 μm², and is saturated with oil with viscosity of 710 mPa·s under reservoir conditions.

Experience in the Application of Reservoir Development Technologies

Over the history of the development of the facility, significant experience has been accumulated in the implementation of various technologies for oil production and injection of coolants.

There are no ready-made technologies for the deposit under consideration. Testing various approaches to development made it possible to identify the most effective of them. The search is carried out mainly in the classical direction – these are thermal methods [1–4]. It is the heating of reservoir oil that gives the greatest technological effect by reducing viscosity (Fig. 1) and increasing the mobility of oil in reservoir conditions [5, 6].

It is advisable to assess the efficiency of the use of various coolants in the conditions of filtration heterogeneity of the reservoir based on the data of implementation in field conditions. Laboratory experiments on the core are not able to cover the entire variety of forms of void space, especially the fracture component. The role of the latter largely depends on the value of reservoir pressure. As the difference between reservoir and lateral rock pressure decreases, the fracture coverage ratio drops and the fracture compression deformation becomes higher. A decrease in the degree of fracture opening has an impact on well flow rates [7–25]. The impact of these processes in laboratory conditions is problematic to assess.

In different periods of time, several types of coolant were used at the facility in different areas of the deposit. For three technologies of thermal areal impact, the predicted oil recovery factor (ORF) was estimated: steam injection at temperature 300 °C, injection of hot water of 210 °C, injection of heated up to 90 °C water. The value of the predicted oil recovery factor is obtained by averaging the results of calculations by displacement characteristics of B.F. Sazonov, G.S. Kambarov, N.V. Sipachev, L.G. Pasevich and S.N. Nazarov.

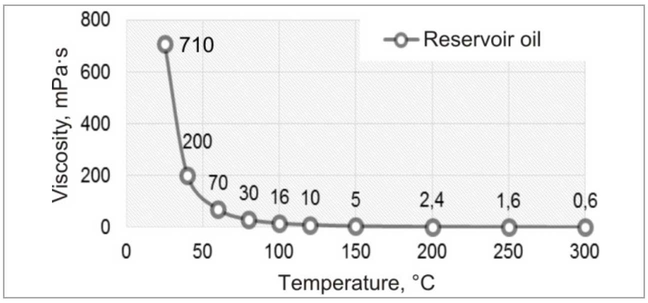

Fig. 1. Dependence of reservoir oil viscosity on temperature

The highest predicted oil recovery factor of 0.42 decimal units was obtained using steam injection technology with a temperature of 300 °C. Steam, in comparison with hot water, has an increased enthalpy, contributes to capillary impregnation of the rock matrix, and a larger volume of the formation is treated, which makes steam injection preferable. However, the use of area steam injection technology is energetically and financially expensive, so its application is limited.

In the case of using the technology of injecting heated water with the temperature of the working agent on the surface of 90 °C the predicted oil recovery factor is 0.22 decimal units. Relatively low temperature of the coolant according to the data of fibre optic system does not exceed 65 °C in the perforation intervals of injection wells and, accordingly, a small area of reservoir heating does not allow achieving a significant oil recovery factor.

The technology of hot water injection with the temperature of 210 °C makes possible to achieve a higher oil recovery factor (0.27 decimal units) in comparison with water heated up to 90 °C and requires less cost in comparison with steam injection; for these reasons it is promising.

Injection of Hot Water with a Temperature of 210 °C

The application of the 210 °C hot water injection technology was based on the results of laboratory core tests in 2012–2015. The displacement coefficient obtained with 210 °C hot water injection was 0.51 decimal units and corresponded to the displacement coefficient obtained with steam injection at 300 °C. Thus, according to the results of filtration experiments for the considered deposit it is proved that it is not necessary to spend energy to bring the agent temperature up to 300 °C, when heating at 90 °C lower provides the the same effect (see Fig. 1). The results of these studies served as an impetus for testing the technology in the deposit.

In order to assess the efficiency of the 210 °C hot water injection technology in the steady-state mode, pilot operations were carried out at the pilot site in the period 2020–2021. The technology consisted of thermal and hydrodynamic impact on the reservoir by area injection of 210 °C hot water.

The application of the new technology was aimed at providing compensation of withdrawals in the area previously developed in the natural operating mode to restore reservoir energy and increase the displacement ratio by changing oil mobility. To increase the coefficient of flooding coverage a chemical composition was used to reduce the the receiving capacity of highly permeable channels.

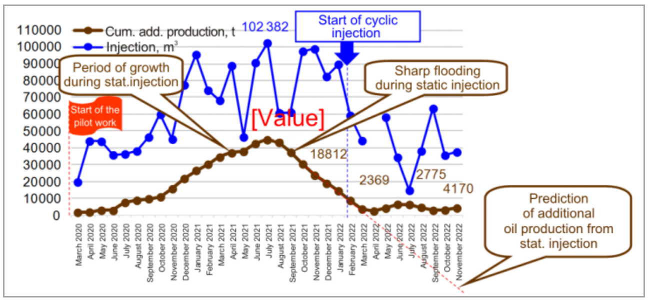

Fig. 2. Dynamics of accumulated additional oil production from hot water injection

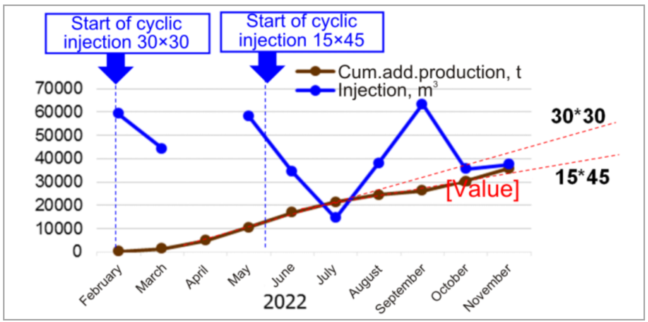

Fig. 3. Dynamics of accumulated additional oil production under cyclic injection mode

In fact, the technology was implemented in three modes: stationary injection in the period 2020–2021 and cyclic injection with sequential application of the modes "30 for 30 days" and "15 for 45 days" (2022).

The dynamics of cumulative production from stationary hot water injection shows that the technology does not confirm its efficiency (Fig. 2). Water breakthrough was obtained due to high filtration heterogeneity of the reservoir. The additional production volume achieved in the initial period was then completely levelled off due to higher water cut rates in the subsequent period.

After the completion of the pilot development hot water injection was continued, but in a cyclic mode. It should be noted that the cumulative additional oil production from cyclic injection is comparable to the maximum cumulative production from stationary injection (see Fig. 2).

The technology of non-stationary injection has shown greater efficiency due to involving in the development matrix reserves which were not drained under the stationary injection mode. Two cyclic injection modes were tested – "30 for 30 days" and "15 for 45 days". The "30 by 30 days" regime has great potential, as it is characterized by a high growth rate of additional oil production compared to the "15 by 45 days" regime (Fig. 3).

Thermal methods of enhanced oil recovery are promising in conditions of highly-viscous oil production. The technology of hot water injection at the deposit under consideration is in general the right direction of development. The rational solution in this case is to take into account the negative experience of the technology and its adaptation to the conditions of realization.

Review of domestic and foreign scientific papers [2, 27, 28] showed a small volume of publications on the issue of hot water injection in cyclic mode in carbonate reservoirs saturated with highly-viscous oil. Most publications are limited to the calculation of cyclic mode on the hydrodynamic model, and there is no description of non-stationary mode realisation in field conditions.

The accumulated world experience in the development of highly – viscous oil deposits is focused mainly on terrigenous reservoirs. There are much fewer deposits of highly-viscous oil in carbonate reservoirs compared to terrigenous reservoirs. Accordingly, experience in the development of carbonate deposits is limited.

In particular, the technology of cyclic injection of hot water in carbonate reservoirs of highly-viscous oil is not sufficiently studied in the world.

In Udmurtia, thermopolymer and thermocyclic technologies for injecting hot water into a carbonate reservoir of highly- viscous oil have been tested and implemented on the industrial scale. New technologies make it possible to achieve the oil recovery factor of 40–45 %, while traditional waterflooding technology can achieve a maximum of 25 %.

Complex Technology of Cyclic hot Water Injection

The authors of the article have developed a new strategy for applying the technology of hot water injection to deposits. Proposed complex technology is based on the following:

1. Cyclic injection mode "30 by 30 days" as the most effective areal method of influencing a fractured formation.
2. Application of chemical composition in injection wells to level the displacement front and prevent water breakthroughs into production wells.
3. Limitation of the volume of produced water to reduce unproductive injection and reduce the water-oil factor.

Hheterogeneous in permeability reservoir, saturated with high-viscosity oil, is a favorable object for the use of non-stationary stimulation [28]. In the case where there is a developed fracture system at the facility, the contact area of the highly permeable filtration channels with the low-permeability matrix may be sufficient to obtain additional oil production [29–33].

One of the key parameters that is controlled in the implementation of non-stationary flooding is the duration of the half-life [28].

The justification of the cyclic hot water injection regime was based on:

– geological and field analysis of the effect of different duration of injection well shutdowns on the producing well stock;

– analytical dependence, which allows estimating the half-period value from the data of piezoconductivity value and distance between a pair of wells (Fig. 4).

The calculation of the half-period value is performed by the formula obtained by V.N. Shchelkachev [37]:

$$t = \frac{l^2}{2\chi},$$

where l – the distance between productive and injection wells, m; χ – piezoconductivity of the reservoir, m^2/s.

The presence of two dependencies in Fig. 4 is explained by the remoteness of the production well from the injection well. As you move away from the active well, the value of the pressure pulse downgrades. In addition, as the distance becomes larger the influence of reservoir heterogeneity increases - cohesion, macro inhomogeneity (including cracks), which creates additional filtration resistances.

Fig. 5 shows the dependences of the half-cycle on the distance between the injection and production wells. The identified groups of wells in Fig. 4 and 5 are identical. It can be seen that group No 1 is

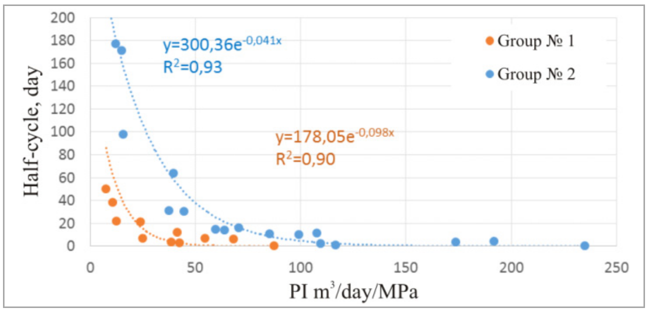

Fig. 4. Dependence of the half-cycle of cyclic injection from the well productivity coefficient

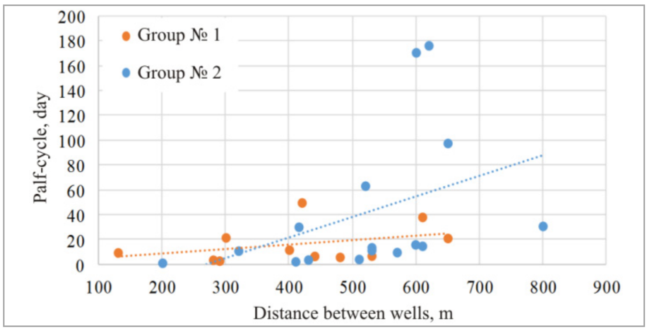

Fig. 5. Dependence of half-cycle on the distance between wells

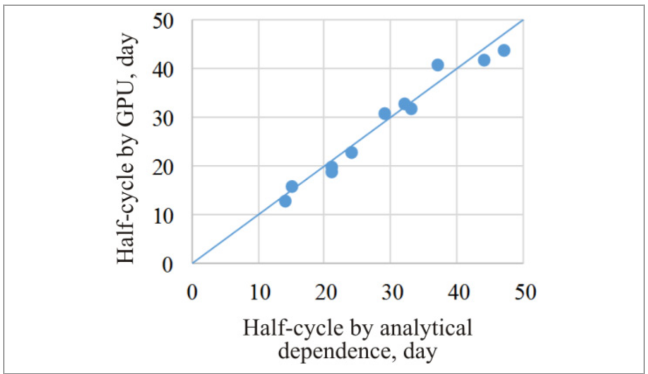

Fig. 6. Cross-plot by half-cycle

characterized by relatively low half-cycle values, while group No 2 has a significant increase in half-life with increasing distance. When determining the half-period of the non-stationary injection mode, it is assumed that the equation of group No 1 is valid at the location of the production well from the active well up to 350 m, and at the distance of more than 350 m – the equation of group No 2.

To determine the half-cycle value for each injection well centre, a list of reacting wells (approximately 20 % of the producing wells in the centre), which gave 80 % of additional oil production from hot water injection (Pareto principle), was identified. According to the list of wells which gave the main additional production, the maximum value of the half-cycle was determined. The maximum value ensures compliance with the condition that all the most important wells in the centre will react to the change in the injection well operation mode.

The result of comparing the half-cycle by both methods showed high convergence (Fig. 6), which allows us to speak about the reliability of the obtained results. For all injection wells of the experimental area a single half-cycle value of 30 days was determined.

For redistribution of filtration flows under conditions of heat transfer fluid injection on deposits ‘intelligent’ gel-forming chemical compositions are used. The essence of chemical compositions development [35] is to create systems which are able to chemically evolve in the reservoir with the acquisition of colloidal-chemical properties optimal from the point of view of oil displacement. Thermotropic systems under the influence of thermal energy of the thermal fluid injected into the reservoir are converted into gels without thickening agent [36–40].

The choice of chemical composition for the proposed complex technology is based on the experience of application of two types of gel-forming compositions at the deposit. The chemical compositions under consideration are thermotropic, capable of operating at temperatures up to 300 °C, which meets the conditions of application of the proposed integrated technology – hot water injection at a temperature of 210 °C. For levelling of injectivity profile it was chosen the composition with the greatest experience of application for solving similar problems on the deposit, characterised by lower cost and at the same time higher value of specific additional oil production per well. In addition, the results of field geophysical studies after injection of the selected chemical composition show the levelling of injectivity profile and its fixation in time, which meets the requirements for the chemical composition.

In order to solve the problem of reducing the volume of produced water at the pilot site, the stock of unprofitable high-watered wells was considered. A list of 25 wells with a total liquid flow rate of 5052 m^3/day was formed, which is about 35 % of the total indicator for the area. It should be noted that mass shutdown of high-yield watered wells in the deposit under consideration, as field experience has shown [41], is accompanied by the phenomenon of interference [42, 43]. The effect of fluid redistribution in the reservoir between the inactive wells and their surroundings was also taken into account during the research.

The technological feasibility of shutting down selected unprofitable high-yield wells was assessed. The results of calculations of the current and forecast conditions of well operation at the clusters where it is planned to shut down unprofitable wells confirm the preservation of the conditions for the hydraulic transportation of products through field pipelines – the current and expected water cut of production in well clusters is more than 70 %.

Assessment of Technological Efficiency of the Complex Technology

The forecast of the technological efficiency of the complex technology developed by the authors of the article is carried out using a geological and technological model (GTM).

The simulated object of development is confined to the trap of a complex structure. The layers are zonally heterogeneous, some of them have a discontinuous character, zones of reservoir replacement with dense rocks have been identified. The completeness and quality of the initial data were sufficient to build a detailed geological model. The distribution of parameters in the reservoir volume was carried out by the method of stochastic modeling. In constructing the structural and tectonic framework, it was taken into account many discontinuous faults, identified by the results of interpretation of 3D seismic surveys and detailed correlation of wells.

The filtration model of the reservoir is three-phase (oil, water, gas), three-component (oil, water, gas dissolved in oil), non-isothermal. To set up the model, the results of laboratory studies of own core samples and reservoir oil were used. The results of filtration studies during the injection of the thermal fluid were taken into account.

To simulate the integrated technology, the authors of the article have developed an algorithm for predicting technological indicators at well interventions, taking into account the effect of injection of a chemical composition on the injectivity profile and ensuring a stable energy state during the cyclic injection mode.

Predictive calculations of technological development indicators were carried out in the sector of the reservoir GTM (Fig. 7).

Creation and adaptation of the geological-technological model were performed in accordance with the methodological recommendations of the Regulations on creation of permanent geological-technological models of oil and gas and oil fields [44]. According to the results of the sector adjustment, the technological parameters of operation were within the limits of permissible deviations.

Modelling of injectivity profile levelling (LIP) of injection wells due to injection of chemical composition was performed by changing the ‘well – reservoir’ connectivity in well perforation intervals. The communicability value was changed so as to satisfy two conditions: the potential injectivity of the well decreased by 17 %, and the injectivity profile levelling was ensured.

Reduction of injectivity by 17 % at modelling complex technology of hot water injection is based on the results of injection of the selected chemical composition into wells located in similar geological and physical conditions relative to the experimental site. Similar reservoir characteristics make possible to draw analogies on the efficiency of chemical composition injection.

The effect of modelling the injectivity profile levelling due to chemical composition injection was assessed by instantaneous injectivity of injection wells. An example of modelling the injectivity profile levelling after chemical composition injection is shown in Fig. 8.

Modelling of cyclic hot water injection in the ‘30 on 30 days’ mode was performed taking into account annual shutdown of the working agent preparation unit for maintenance.

In order to ensure a stable energy state in the forecast period, injection volumes were calculated in the set compensation mode. At small gradients of pressure only water will be mobile, so it is important to ensure an acceptable reservoir pressure level [29–33].

The experimental area was divided into 11 groups, each group consisting of an injection well and a list of surrounding production wells. For each group, the level of withdrawal compensation required to maintain reservoir pressure was set. This compensation value was determined by hot water injection during the period when stable dynamics of technological indicators (including dynamic level) was observed, which poined to a steady-state operation mode and, accordingly, stable reservoir pressure. The compensation value was determined during steady-state injection, therefore, for non-steady injection mode the compensation was doubled.

Four expected variants of calculation of technological indicators from 01.01.2023 to 01.01.2034 were performed:

– variant 1 – operation of the site in the natural elastic-water-drive regime;

– variant 2 – operation of the site in a permanent hot water injection mode from 01.01.2024;

– variant 3 – operation of the site in cyclic mode ‘30 on 30 days’ of hot water injection from 01.01.2024;

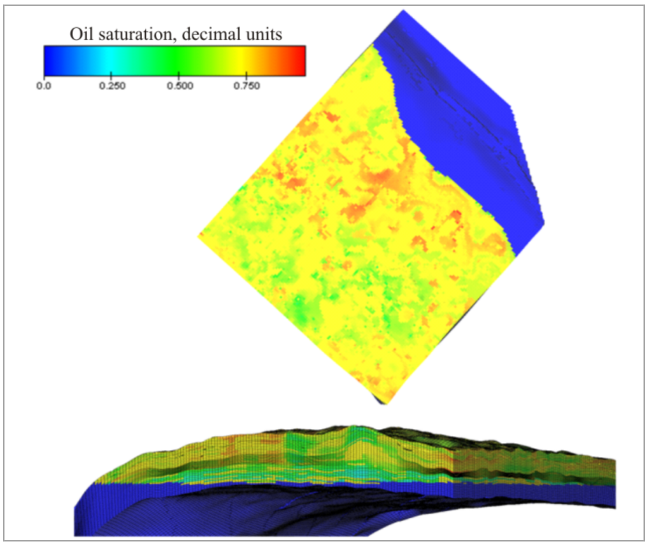

Fig. 7. Appearance and section of the geological and technological model sector on the example of the field of the current oil saturation distribution

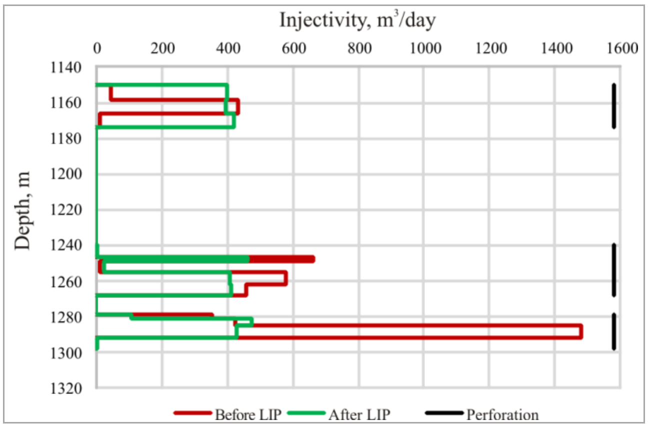

Fig. 8. Example of modelling the injectivity profile levelling after chemical injection

– variant 4 – operation of the site in cyclic mode ‘30 on 30 days’ of hot water injection from 01.01.2024 with shutdown of unprofitable wells from 01.01.2024.

The calculations were carried out in the mode of constraints: injectivity/flow rate of well fluid; BHP; temperature of the heat carrier; specified compensations; minimum oil flow rate, upon reaching which the well is transferred to an inactive stock.

The cumulative production indicators for the wells of the pilot site as of January 1, 2024 in the context of expected variants are presented in the table. In this article, the calculations of indicators are demonstrated with the conditional values of the initial and calculated parameters, any coincidences with the real values of production indicators are accidental.

The analysis of the technological indicators of the development according to the considered options allows us to conclude that the proposed integrated technology for cyclic injection of hot water is the most effective among those considered. The variant is characterized by the most favorable dynamics of watering, allows to reduce the volume of associated produced and injected water. Reduction of the existing stock of producing wells due to the shutdown of unprofitable high-yield wells will reduce the cost of servicing the well stock and maintaining them in working order.

Non-stationary flooding makes it possible to improve the efficiency of reserves recovery by initiating the exchange of fluids between pore blocks and fractures [28] due to the created variable pressure gradient, while stationary injection allows to involve oil reserves only in the most permeable intervals. Cumulative additional oil production for 10 years of implementation of the integrated cyclic injection technology will amount to 323 thousand tons, and the reduction in fluid production will be 614 thousand tons. Due to cyclic injection of hot water in 2022 (one year), additional oil production in the amount of 35.8 thousand tons was obtained. Fig. 13 shows examples of the dynamics of changes in reservoir temperature in the area of three producing wells at the expense of effects of cyclic hot water injection. The trend of reservoir temperature increase in the area of well No 1 shows a cyclic mode of reservoir heating and cooling depending on the operation of injection wells with a frequency of "30 to 30 days".

An increase in the temperature of produced products will facilitate the transportation of high-viscosity oil through field pipelines. In general, adaptation of field facilityt is not required for the implementation of the proposed technology. The composition of the facilities and their capacity meet the requirements of the proposed technology.

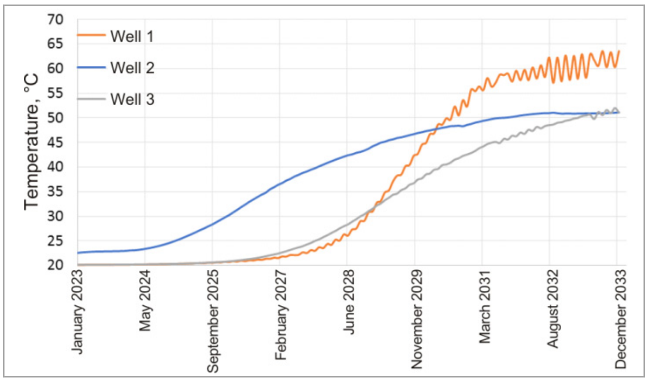

Fig. 13. Examples of dynamics of reservoir temperature change of production wells due to the effect of cyclic hot water injection

Cumulative production indicators by wells of the pilot site as of 01.01.2024 by the expected variants

Indicators as of 01.01.2024 by the pilot site	Variants of calculation			
	Natural	Stat. injection	Cycle injection	Cycle injection with inactive prod.well
Cumulative oil production, kt	20 539	20 863	20 930	20 862
Cumulative fluidl production, kt	120 088	128 184	126 017	119 474

Conclusion

Based on the results of geological and field analysis of the efficiency of stationary and non-stationary modes of operation of the reservoir pressure maintenance system under which hot water injection was carried out during the development of carbonate deposit of the Timan-Pechora oil and gas bearing province saturated with super-viscous oil and having significant geological heterogeneity, a complex technology of hot water injection is proposed. It is based on the following:

1. Cyclic injection mode '30 on 30 days' as the most effective area method of impact on the fractured reservoir.
2. Application of chemical composition for levelling the displacement front and prevention of water breakthrough into production wells.
3. Limitation of the produced water volume to reduce unproductive injection and increase the water-oil factor.

In conditions of high water cut optimization of the injection technology will increase the rate of extraction of residual oil reserves and reduce the volume of produced water. Also it will give the growth of economic efficiency of development at the deposit in question by reducing operating costs.

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