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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық рефераттивтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық рефераттивтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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EVALUATION OF THE EFFECTIVENESS OF CYCLIC STIMULATION AT THE FIELDS OF WESTERN KAZAKHSTAN

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Abstract. *Relevance.* At the late stages of development of most oil fields in Kazakhstan and abroad, a significant portion of the original geological oil resources remains in the reservoir after the extraction of nearly all recoverable reserves. Current production rates are only partially compensated by additions from new discoveries, which makes the implementation of enhanced oil recovery methods that do not require substantial capital investments a priority. One of the most promising approaches is non-stationary (cyclic) waterflooding, which allows the redistribution of filtration flows, involvement of poorly drained zones, and increased efficiency of oil displacement in heterogeneous reservoirs. *Objective.* This study evaluates the effectiveness of cyclic stimulation using a field case characterized by high reservoir heterogeneity, elevated water cut in the producing wells, and the presence of stagnant zones. *Methods.* Based on the analysis of the reservoir's geological and physical characteristics, the structure of the current waterflooding system, and development dynamics, a pilot implementation of cyclic waterflooding was carried out with variations in injection/shut-in cycles, injection volumes, and the configuration of active injector wells. The filtration flow behavior and the presence of an extensive fracture network were confirmed by tracer studies, which recorded rapid tracers breakthroughs to producing wells. *Results.* The results demonstrated a redistribution of displacement fronts, a reduction in the water cut of producing wells, and additional incremental oil production compared to a conventional stationary waterflooding regime. The most pronounced effect was achieved by alternating periods of active injection with pressure-decline phases, which promoted the involvement of low-permeability layers and previously bypassed zones. *Conclusions.* The evaluation confirms the high potential of non-stationary waterflooding for mature and highly watered-out fields. The method can be integrated into the existing pressure maintenance system without significant costs, providing additional oil recovery through more uniform reservoir sweep and optimization of filtration flow patterns.

Keywords: cyclic waterflooding, matrix, reservoir, enhanced oil recovery, unsteady waterflooding, tracer studies

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БАТЫС ҚАЗАҚСТАН КЕН ОРЫНДАРЫНДА ЦИКЛДІК ӘСЕР ЕТУДІҢ ТИІМДІЛІГІН БАҒАЛАУ

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Аннотация. *Өзіктілігі.* Қазақстандағы және шетелдегі кен орындарының басым бөлігін игерудің соңғы кезеңдерінде өндіруге болатын қорлар іс жүзінде толық алынғаннан кейін жер қойнауында бастапқы геологиялық мұнай ресурстарының біршама бөлігі қалып қояды. Өндіру қарқыны жаңа қорлардың өсуімен тек жартылай ғана өтеледі, бұл айтарлықтай капиталдық шығындардыталапетпейтінмұнайбергіштіктіарттыруәдістеріненгізудібасым бағытқа айналдырады. Перспективалы әдістердің бірі – сүзгілік ағындарды қайта бөлуді, әлсіз дренаждалатын аймақтарды игеруге қосуды және әртекті қабаттардан мұнайды ығыстыру тиімділігін арттыруды қамтамасыз ететін станционарлық емес(циклдік) су айдау болып табылады. Мақсаты. Мақалада коллекторлардың жоғары гетерогенділігімен, өндіруші қордың сулануымен және тоқырау аймақтарының болуымен сипатталатын объектінің мысалында циклдік әсердің тиімділігі бағаланды. Әдістері. Қабаттардың геологиялық-физикалық сипаттамаларын, қолданыстағы су айдау жүйесінің құрылымын және игеру динамикасын талдау негізінде айдау/тоқтату циклдерін, айдалатын көлемдерді және белсенді айдау ұңғымаларының конфигурациясын өзгерте отырып, циклдік су айдауды тәжірибелік енгізу жүзеге асырылды. Сүзгілік ағындардың ерекшелігі мен дамыған трещиналар желісінің болуы өндіруші ұңғымаларға индикатордың жылдам серпінді өтуін тіркеген трассерлік зерттеулердің нәтижелерімен расталды. Нәтижелері. Алынған нәтижелер ығыстыру фронттарының қайта бөлінгенін, өндіруші ұңғымалардың сулану қарқынының төмендегенін және тұрақты су айдаумен салыстырғанда мұнай өндірудің қосымша өскенін көрсетті. Белгілі болғандай, ең жоғары тиімділік айдаудың белсенді кезеңдерін қысым төмендеу фазаларымен алмастырған кезде байқалады. Мұндай режим төмен өткізгішті қабаттарды және бұған дейін сүзгілеу процесіне қатыспаған аймақтарды жұмысқа тартуға мүмкіндік береді. Қорытынды. Жүргізілген бағалау тұрақсыз су айдауды жетілген және сулануы жоғары кен орындарында қолданудың перспективалылығын растайды. Әдісті қабат қысымын ұстап тұрудың қолданыстағы жүйесіне біршама шығындарсыз енгізуге болады және ол қабатты неғұрлым біркелкі қамту мен ағындар құрылымын жақсарту есебінен мұнайбергіштіктің артуын қамтамасыз етеді.

Түйін сөздер: циклдік су айдау, матрица, коллектор, мұнай бергіштігін арттыру, стационарлы емес су айдау, трассерлік зерттеулер

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ОЦЕНКА ЭФФЕКТИВНОСТИ ЦИКЛИЧЕСКОГО ВОЗДЕЙСТВИЯ НА МЕСТОРОЖДЕНИЯХ ЗАПАДНОГО КАЗАХСТАНА

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Аннотация. Актуальность. На поздних стадиях разработки большинства месторождений Казахстана и зарубежных стран после отбора значительной части извлекаемых запасов в недрах остается существенная доля начальных геологических ресурсов нефти. Темпы добычи лишь частично компенсируются приростом новых запасов, что делает приоритетным внедрение методов увеличения нефтеотдачи, не требующих значительных капитальных вложений. Одним из наиболее перспективных методов является нестационарное, или циклическое, заводнение, позволяющее перераспределять фильтрационные потоки, вовлекать в разработку слабодренируемые зоны и повышать эффективность вытеснения нефти из неоднородных пластов. *Цель*. Оценить эффективность циклического воздействия на примере объекта, характеризующегося высокой неоднородностью коллекторов, обводненностью добывающего фонда и наличием застойных зон. *Методы*. На основе анализа геолого-физических характеристик пластов, структуры текущей системы заводнения и динамики разработки проведено опытное внедрение циклического заводнения с варьированием циклов закачки и остановки, объемов нагнетания и конфигурации активных нагнетательных скважин. Специфика фильтрационных потоков и наличие развитой сети трещин были подтверждены результатами индикаторных, или трассерных, исследований, зафиксировавших быстрые прорывы индикатора к добывающим скважинам. *Результаты и выводы*. Полученные результаты показали перераспределение фронтов вытеснения, снижение темпов обводнения добывающих скважин и дополнительный прирост добычи нефти по сравнению со стационарным заводнением. Установлено, что наиболее значимый эффект достигается в низкопроницаемых пропластках и зонах, ранее не участвовавших в фильтрации. Проведенная оценка подтверждает перспективность применения нестационарного заводнения на зрелых и высокообводненных месторождениях. Метод может быть внедрен в действующую систему поддержания пластового давления без существенных дополнительных затрат и обеспечивает прирост нефтеотдачи за счет более равномерного охвата пласта и улучшения структуры фильтрационных потоков.

Ключевые слова: циклическое заводнение, матрица, коллектор, методы увеличения нефтеотдачи (МУН), нестационарное заводнение, трассерные исследования

Introduction. A characteristic feature of the current stage is the increasing volume of reserves at a late stage of development, accompanied by a sharp change in their structure. The depletion level of active reserves has reached 65.5%, and that of hard-to-recover reserves is 23% (Gavura et.al., 1995).

Under these conditions, to improve the efficiency of waterflooding systems, a particularly important role in recent years has been played by one type of reservoir pressure maintenance—unsteady (cyclic) waterflooding, which makes it possible to increase reservoir sweep efficiency.Improving the cyclic stimulation method, as well as the method of altering filtration flow directions and integrating them with physicochemical techniques, will make it possible to enhance the efficiency of field development in both the early and late stages (Gavura et.al., 1995).

The term 'unsteady waterflooding' is often used in a generalized sense and refers to cyclic waterflooding based on the periodic variation of injection regimes, up to a complete shutdown of injection. Positive results of cyclic waterflooding were obtained in the US at the Spraberry and Martenville fields. In Germany, cyclic water injection was carried out at the Reinkenhagen field. In the former Czechoslovakia, cyclic waterflooding was also successfully applied at the Hrušky-Sever field. In Russia, there are many fields with a significant amount of remaining recoverable reserves, characterized by advanced recovery from initial recoverable reserves with a water cut of 1.5–2 times. The main objective for such fields at the moment is to reduce the water cut of the produced products in order to increase oil production and reduce the costs of associated water disposal. Cyclic waterflooding is one of the most economically viable enhanced oil recovery methods for such fields. An understanding of the rational choice of an object with high potential for the application of unsteady-state waterflooding is necessary (Chikirov et.al., 2019).

The unsteady waterflooding method is widely applied at oil fields in Tatarstan, Western Siberia, Bashkortostan, and others. The main advantages of this method are its simplicity of implementation, its broad applicability under various reservoir conditions, as well as its cost-effectiveness and efficiency. To date, there is extensive experience in theoretical, experimental, and field studies. Considering that a large number of fields are at a late stage of development, it is necessary to improve and enhance the performance of the unsteady waterflooding technology (Farrakhov et.al., 2020).

The following factors influence the effectiveness of unsteady-state waterflooding: 1) elasticity, wettability, water saturation of the reservoirs; 2) heterogeneity in permeability; 3) degree of hydrodynamic connectivity of the layers; 4) duration of half-cycles; 5) amplitude of fluctuations in the injected water flow rate; 6) duration of preceding steady-state waterflooding. It is impossible to significantly influence the first three factors. The amplitude of fluctuations and the duration of preceding waterflooding depend on the development history; these can also be influenced only slightly at present. However, the duration of the half-cycles can be varied; therefore, the question arises of substantiating the optimal duration of the half-cycles of unsteady-state waterflooding (Kashapova, 2017).

Analysis of the development of carbonate reservoirs at oil fields has made it possible to identify several features of reserve depletion and to assess the effectiveness of unsteady waterflooding. It has been established that, unlike terrigenous reservoirs, these reservoirs have a significantly lower oil recovery factor.

Studies of wells using tracer injection, production logging methods, thermometry, and oil photocolorimetry have made it possible to outline solutions to a number of issues related to defining development targets, determining current reserve depletion, monitoring the rise of the oil–water contact, and others (Malysheva et.al., 2018).

With the growing prevalence of the waterflooding method and its implementation at an increasing number of oil fields, it was observed that the periodic shutdown and resumption of water injection positively affects the productivity of producing wells, reduces their water cut, and ultimately increases reservoir oil recovery.

Compared to other enhanced oil recovery methods, the technology of cyclic waterflooding is currently the most thoroughly studied and widely applied in the field. The successful implementation of the method has been facilitated by the research of scientists such as Surguchyov, Ogadzhanyants V.G., Bokserman A.A., Tsinkova O.E., Sharbatova I.N., Shalimov B.V., and others. The method is characterized by its simplicity, the possibility of application across a wide range of reservoir conditions, and its high economic efficiency.

Analysis of oil field development has shown that with periodic changes in injection and production regimes, not only does the rate of oil production increase, but the water cut of the produced fluids is also significantly reduced. M.L.Surguchyov explained this by noting that periodic waterflooding in heterogeneous reservoirs promotes the transfer of water from high-permeability to low-permeability zones, thereby increasing the sweep efficiency of the reservoir. As early as 1959, he was the first to develop the method of cyclic reservoir stimulation. This contributed to the development of methods for preventing well watering by regulating reservoir development through partial or complete modification of the displacement system (Malysheva et.al., 2018).

According to numerous laboratory studies on water-driven oil displacement, the main types of residual oil saturation are:

— capillary-trapped oil;

— sorbed oil;

— film (film-bound) oil;

— oil remaining in isolated zones that are not swept or only partially swept by waterflooding (Nuranbayeva et.al., 2021).

Residual geological oil reserves that are not swept by waterflooding due to significant reservoir heterogeneity in filtration–capacity properties, high compartmentalization, and sharp discontinuity of layers across the area and section, remain in the formation in the form of capillary-trapped oil and residual isolated pockets. This category of residual oil saturation accounts for about 70% of all remaining oil reserves and represents the main potential for increasing reservoir oil recovery (Medvedev et.al., 2017).

The effectiveness of unsteady waterflooding in the development of reservoirs heterogeneous in permeability has led to the widespread application of this technology. Its effect is manifested in the redistribution of reservoir pressure between interlayers and the increased recovery of oil reserves from low-permeability layers. Moreover, the stronger the reservoir heterogeneity, the more significant the effect of unsteady waterflooding technology (Abzalov et.al., 2020).

In the case of steady-state waterflooding, the presence of fracturing in the reservoir leads to rapid water breakthrough into production wells and to a reduction in the oil recovery factor. The use of unsteady waterflooding makes it possible to increase oil production. At the same time, unsteady waterflooding in a homogeneous reservoir does not lead to a significant increase in oil recovery.

The effectiveness of unsteady waterflooding strongly depends on the permeability and the orientation of fractures relative to the wells. A strong effect from unsteady waterflooding may serve as an indication of the presence of fractures in the reservoir (Pyatkov et.al., 2018).

The main principle of the unsteady waterflooding technology is as follows. The method provides for increasing the elastic energy of the reservoir system by periodically raising and lowering the water injection pressure. This creates the prerequisites for the development of unsteady pressure differentials within the reservoir and corresponding unsteady fluid crossflows between layers (zones) of different permeability. In the half-cycle of increased injection pressure, water from the higher-permeability layers penetrates into the low-permeability layers, while in the half-cycle of decreased pressure, oil from the low-permeability interlayers moves into the high-permeability part of the reservoir.

Unsteady waterflooding is often combined with technologies for altering the direction of filtration flows. In such cases, the combination of technologies results in an effect driven both by the unsteady processes within the reservoir and by the change in the direction of dominant flow paths of reservoir fluids. The integrated technology allows an increase in reservoir sweep both vertically and laterally.

In practice, an unsteady pressure field is created through the periodic shutdown (or variation in injectivity) of injection wells and/or the periodic shutdown of highly water-cut production wells. Methods for creating periodic pressure oscillations may be combined, for example, through cyclic water injection and periodic operation of production wells in counterphase with the injection wells.

The main advantage of unsteady waterflooding is its low cost; the implementation of the technology requires no capital expenditures and does not increase operating costs. At the same time, its application yields a significant effect. According to expert assessments conducted at several oil fields where unsteady waterflooding was applied, the resulting incremental effect ranges from 8% to 14% of the cumulative oil production over the period of technology implementation.

The effectiveness of unsteady waterflooding is determined by many parameters, including reservoir permeability heterogeneity, initial water cut of produced fluids, the viscosity ratio of oil to water, the amplitude of the impact (from injection wells), the duration of shutdown and operating periods of injection and production wells, the type of waterflooding system, and others (Vladimirov et.al., 2018).

The implementation of this method does not require significant capital or operating expenditures, which increases the likelihood of its application. There are also data confirming the successful use of unsteady reservoir stimulation technology in heterogeneous formations. The essence of the technology lies in the artificial generation of alternating pressure differentials between parts of the reservoir at specified time intervals. This is achieved by periodically shutting in and restarting injection wells with a predetermined cycle duration.

These pressure differentials cause a redistribution of the reservoir fluids, promoting the equalization of their saturations and the balancing of capillary pressures at the boundary between waterflooded and oil-saturated zones. As a result of this process, accelerated countercurrent imbibition of water into oil-saturated zones is observed between regions of different saturation; in other words, water from the flooded zones penetrates into the oil-saturated areas through channels of smaller cross-sectional size, facilitating the displacement of oil from them (Ilyushin et.al., 2022).

Materials and мethods. Modern trends in the development of Kazakhstan's oil production industry are characterized by an increasing share of hard-to-recover reserves and the late stage of development of many currently producing fields. Addressing the challenge of maintaining oil production levels requires the identification of efficient and economically viable enhanced oil recovery (EOR) technologies. One of the relatively low-cost hydrodynamic EOR methods is cyclic flooding, which makes it possible to achieve the following key objectives:

– increase the areal and vertical sweep efficiency of the reservoir;

– reduce the residual oil saturation;

– improve the oil recovery factor with minimal operating expenditures.

Analysis of field applications of cyclic flooding demonstrates that this method can increase oil production by 3–6% over the forecast period compared with conventional continuous waterflooding.

As part of the present study, the effectiveness of implementing cyclic waterflooding technology was examined at an oil field with a reservoir located in the lower carbonate sequence KT-II (Upper Visean–Kashir age, 3013–3894 m) in Western Kazakhstan, characterized by a complex geological structure with extensive fracturing.

The commercial oil and gas potential of the field is associated with subsalt Carboniferous deposits, which include two productive sequences, KT-I and KT-II, separated by a 159.1–1009.4 m intercarbonate interval (ICI), where lens-shaped oil-saturated reservoir layers are also identified in certain areas.

The upper carbonate sequence KT-I, which contains a gas–oil reservoir, is stratigraphically associated with Upper Podolian–Gzhelian deposits and occurs at depths of 1836–4077 m. The sequence is composed of limestones, dolomites, and limestone–dolomite varieties of carbonate rocks, with interbeds of terrigenous rocks, predominantly argillites.

The lower carbonate sequence KT-II, containing the oil reservoir, is associated with Upper Visean–Kashirian deposits at depths of 3013–3894 m and is lithologically represented mainly by limestones with interbeds of greenish-gray argillites.

The intercarbonate interval, corresponding to Upper Moscovian substage deposits, is composed of terrigenous rocks by 50–90%. The total thickness of KT-I varies from 39.1 m to 667.0 m, the intercarbonate interval ranges from 159.1 m to 1009.4 m, and the thickness of KT-II varies from 251.5 m to 895.6 m across the wells.

Many oil fields in Western Kazakhstan face a range of challenges similar to those identified at the field under study. The key factors limiting development efficiency are related both to technological aspects of field operation and to the geological and reservoir characteristics of the productive formations.

The main technological issues include:

– insufficient quality of injection water preparation for reservoir pressure maintenance (RPM);

– significant wear of downhole equipment in the injection well stock.

The geological and development-related challenges include:

– low recovery of reserves, which as of 01.01.2022 amounts to only 37%;

– a significant decline in reservoir pressure to values below the bubble-point pressure (initial pressure — 339 atm, current — 150 atm, bubble-point pressure — 249 atm);

– increasing gas–oil ratio accompanied by declining oil production rates;

– low efficiency of the current RPM system: injection wells do not provide effective oil displacement, and injected water predominantly flows through fracture–cavern channels, rapidly breaking through into producing wells;

– high water cut of produced fluids and frequent water breakthroughs from injector to producer wells;

– low oil recovery factor (ORF): the current ORF is 0.096 over 21 years of development. Under the existing RPM system, the approved project ORF is not achievable, and the expected ORF is approximately twice as low as the approved one;

– Complex geological structure characterized by extensive fracturing, which results in the formation of high-permeability flow channels.

Tracer studies performed at the field confirm the pronounced fracturing of the reservoir. A total of 21 out of 22 injection wells were included in the tracer program. Rapid tracer breakthroughs to distant producing wells were recorded, with the first tracer arrivals detected within a few days. Considering the low reservoir storage and flow properties, such rapid movement indicates the presence of a well-developed fracture network and dominant preferential flow paths.

The obtained tracer data enable the optimization of the RPM system through the implementation of technologies aimed at redistributing injected water flow. One of the promising approaches is cyclic waterflooding, which allows influencing not only the high-permeability channels but also the low-permeability rock matrix through alternating injection and shut-in periods.

A complex geological structure characterized by extensive fracturing. Injected water in the field preferentially flows into high-permeability channels (fractures), bypassing the rock matrix, which is confirmed by tracer studies as shown in Figure 1.

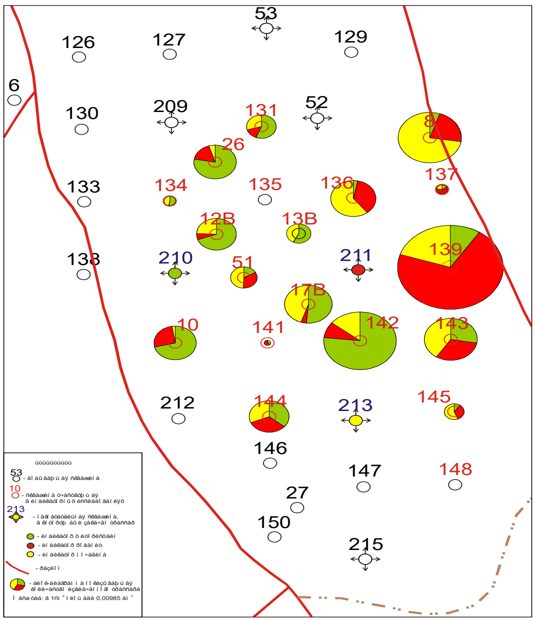

Figure 1. Distribution of Detected Tracers by Volume.
52 – producing well, 10 – well participating in tracer studies, 213 – injection well into which the tracer was injected, -fluorescein tracer, – rhodamine tracer, – urea tracer, 144 - block diagram showing the amount of recovered tracer, - fault.

As can be seen from Figure 2, the tracer studies at the field covered 21 out of 22 injection wells. As a result of the tracer investigations, rapid breakthroughs of tracers to distant producing wells were recorded.

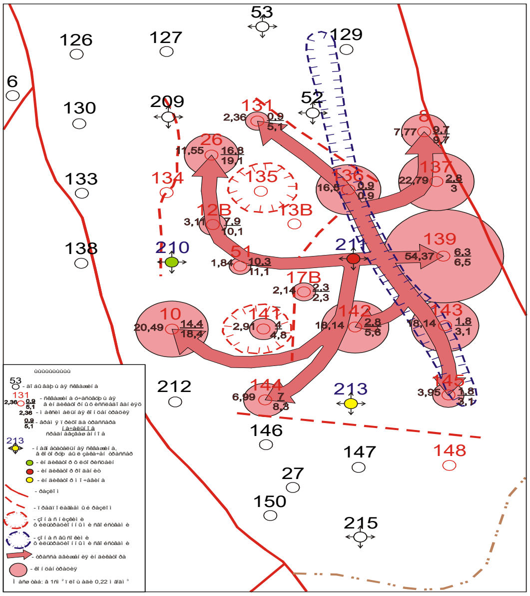

Figure 2. Results of Tracer Studies for Injection Well No. 211 Using Rhodamine Tracer.

53 – producing well, 131 – well participating in the tracer study, 2.36 – maximum concentration, 0.9 days – initial tracer arrival time, 5.1 days – weighted average tracer arrival time.

Based on Figure 2, it can be concluded that the first portions of tracers are detected within a few days. Considering the low filtration–capacity properties of the reservoir, this indicates significant fracturing of the formation.

Using these tracer study data, reservoir pressure maintenance can be optimized through cyclic waterflooding.

The field has a complex geological structure characterized by extensive fracturing. Development of fractured reservoirs is ineffective when using classical waterflooding methods. Maintaining consistently high pressure in the fractures minimizes the potentially high sweep efficiency attributed to the fracture (well). Significant movable oil reserves remain bypassed by the injected water as a result of the current development system. Isolation of water-bearing intervals in wells does not increase displacement across the reservoir; on the contrary, it removes from the development process the intervals with the highest reservoir coverage.

The physical meaning of cyclic stimulation is interpreted as follows: "The method provides for increasing the elastic energy of the reservoir system by periodically raising and lowering the water injection pressure. This creates conditions for the emergence of unsteady pressure gradients within the reservoir and corresponding unsteady fluid crossflows between layers (zones) of different permeability. During the half-cycle of increasing injection pressure, water from high-permeability layers is forced into low-permeability layers, while during the half-cycle of pressure reduction, oil from low-permeability interbeds moves into the high-permeability part of the reservoir" (Baushin et.al., 2023).

In a number of fields, including the one under consideration, the reservoir has a dual nature. The reservoir consists of fractures, which have high permeability, and matrix blocks, where the main portion of oil reserves is contained. Therefore, it is important to understand how fluids move between these two media.

1.Features of a fractured–matrix reservoir.

Fractures serve as fast channels for the flow of water and oil, while the matrix is the main storage of reserves. The key problem is that under conventional waterflooding, water primarily moves through the fractures, leaving the matrix blocks poorly involved in the development process. Thus, the traditional injection regime is not always effective.

2. Two regimes of interaction between water and the matrix.

Figure 3 illustrates how the pressure ratio between the fracture and the matrix affects the process.

Mode 1: pressure in the fracture is higher than pressure in the matrix ($P_f > P_m$).

Under this regime:

– water rapidly breaks through along the fractures;

– matrix reserves are practically not involved;

– water penetrates the matrix only to a shallow depth, forming a so-called water-saturated "rim."

As a result, most of the oil remains in the matrix and is not produced.

Mode 2: pressure in the fracture is lower than pressure in the matrix ($P_f < P_m$).

In this case:

– oil begins to flow from the matrix into the fracture;

– matrix blocks become involved in the development process;

– recovery of reserves increases.

This regime is the desirable one, as it ensures oil inflow from the main part of the rock.

3. Principle of unsteady (cyclic) waterflooding.

To make maximum use of the reservoir's characteristics, unsteady (cyclic) waterflooding is applied. This method is based on alternating cycles:

Water injection period (pressure in the fractures increases);

Injection shutdown (pressure decreases).

Such alternation makes it possible to:

– create pressure differentials between the fractures and the matrix,

– periodically stimulate oil crossflow from the matrix,

– «oscillate» the reservoir similarly to a pump,

– increase the degree of involvement of remaining reserves.

Under steady (continuous) injection, a significant portion of reserves remains non-involved. The pressure difference between fractures and the matrix determines the direction of fluid movement. Alternating injection and shutdown cycles increases oil inflow from the matrix. The unsteady (cyclic) waterflooding method promotes more complete recovery of remaining reserves and increases oil recovery.

This technique is aimed at enhancing oil recovery in fractured reservoirs and improving the efficiency of reservoir pressure maintenance.

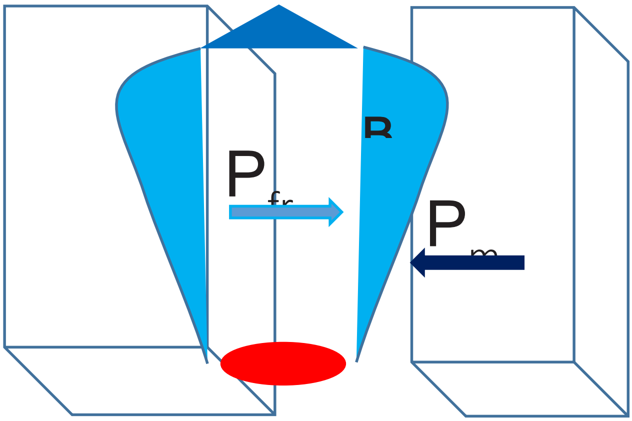

Figure 3. Schematic representation of matrix blocks and a fracture in plan view.

Pilot field tests of non-stationary waterflooding were carried out in the lower carbonate interval KT-II (Upper Visean–Kashirian age, 3013–3894 m), and a positive effect was obtained as shown in Table 1. During the pilot implementation of non-stationary waterflooding in the Northern and Central dome areas of the field, 8 thousand tons of additional oil production were obtained.

The results of the pilot tests indicate that unsteady waterflooding is significantly more effective when the shutdown cycles are multiple times longer than the injection cycles (at least by a factor of two).

In order to maximize oil production rates in the short term and achieve the highest possible oil recovery factor in the long term, unsteady waterflooding can be applied as a well stimulation method for several (3–4) months each year.

Table 1. Evaluation of the Efficiency of Non-Stationary Waterflooding.

Years of cyclic water injection	**1st Year**	**2nd Year**		**3rd Year**		**4th Year**	
Area / Site	North	North	Center	South	Center	North	South
Shutdown cycles	10-15	10-15	10-15	10-15	10-15	4	9
Injection cycles	3	3	3	3	3	9	4
Duration	92	154	123	123	130	125	135
Injection wells	307, 316, 324	307, 316, 324	54, 115	215, 210, 211, 213, 52, 209	54, 108, 115, 201, 204, 205	307, 316, 324	210, 211, 213, 52, 209
Number of responding production wells	2	2	6	20	19	5	19

Cumulative additional oil production, tons	845,6	1903,1	840,6	1698,0	671,0	456,7	1562,7
Effect	+	+	+	+	+	+	+

The pilot implementation of unsteady (cyclic) waterflooding demonstrated the feasibility of applying this method, as well as its effectiveness for individual wells that intersect fractures:

– The displacement pattern changed;

– Water cut decreased;

– Poorly drained reserves were brought into production.

At most oil fields, after near-complete depletion, the remaining oil is retained in the reservoir in the form of thin films or droplets, particularly in water-saturated or low-permeability formations. To enhance the recovery of this residual oil, the method of cyclic (non-stationary) injection is widely used, and it has demonstrated its effectiveness at several fields in Kazakhstan and abroad. Unlike many enhanced oil recovery (EOR) techniques, cyclic injection does not require additional surface infrastructure or the purchase of new equipment, and therefore does not increase the cost of oil production.

Analysis of the geological and physical characteristics of the reservoirs and the existing development systems indicates that this method is suitable for fractured formations. To achieve maximum efficiency from the implementation of cyclic injection, it is recommended to apply the selection criteria and operational procedures proposed in this study.

Results and analysis. During pilot field tests of the non-stationary (cyclic) waterflooding technology applied in the Lower Carbonate Reservoir KT-II, the following results were obtained:

1. Additional oil production.

From 2019 to 2022, the cumulative incremental oil production at the Northern, Central, and Southern areas reached 8 thousand tonnes.

Each tested area demonstrated a positive effect, ranging from 456.7 to 1903.1 tonnes per year, depending on the cycle duration and the number of responding wells.

2. Changes in filtration flow behavior.

Pressure redistribution in the fractured–matrix system was observed:

– during injection cycles, pressure in fractures increased,

– during shut-in cycles, it decreased, which stimulated oil flow from the matrix to the fractures and enhanced oil inflow into producing wells.

3. Reduction in water cut.

Several producing wells showed a decrease in water cut by 3–12%, associated with the weakening of water breakthrough channels and improved drainage of previously undrained zones.

4. Improved reservoir sweep.

The number of producing wells responding to the technology reached 19–20 wells, indicating an expansion of the drainage area and improved lateral sweep efficiency.

5. Strong response from fractured intervals.

The greatest positive response was observed in wells intersecting fractured zones, confirming high sensitivity of fractured reservoirs to non-stationary pressure fields.

6. Optimal cycle ratio identified.

Maximum incremental production was achieved when:

– shut-in cycles lasted 10–15 days,

– injection cycles lasted 3 days, demonstrating the importance of extended depressurization periods for matrix oil drainage.

Discussion of Results. Analysis of the obtained data and comparison with geological and physical reservoir characteristics allow for identifying several key patterns:

1. Efficiency of non-stationary flooding in fractured reservoirs

Fractures have high permeability, causing rapid water breakthrough during conventional waterflooding. This leaves a large portion of oil trapped in the matrix, the primary storage zone.

Cyclic pressure changes:

– temporarily saturate fractures with water during injection,

– create a pressure drop during shut-in periods, leading to oil migration from the matrix into the fractures ($P_{fracture} < P_{matrix}$).

Thus, cyclic flooding effectively restores matrix drainage, which is not achievable under constant-rate injection.

2. Greater incremental oil with longer shut-in periods

The data show that longer injection stoppages result in higher oil recovery. This aligns with the slow pressure equilibration in the matrix blocks—the system requires time to initiate crossflow from matrix to fractures.

3. Reduction in water cut due to cyclic pressure variation

Decreased water production is linked to:

– disruption of stable water breakthrough channels,

– redistribution of flow towards less-drained zones,

– reactivation of matrix-to-fracture oil transfer.

These mechanisms increase the oil fraction in the produced fluids.

4. Improved reservoir sweep

An increase in the number of responding producing wells confirms that cyclic flooding enhances overall system performance and improves sweep both vertically and laterally.

5. Results fully correspond to the theoretical mechanism of cyclic flooding

The observations align with the classic mechanism described by Surguchov and others: the rise in oil recovery is caused by non-stationary pressure gradients and counter-current flows, which are especially significant for fractured reservoirs.

Conclusions. Based on the results of pilot implementation, the following conclusions can be drawn:

1. Unsteady-state waterflooding technology is an effective enhanced oil recovery (EOR) method for fractured-matrix reservoirs of the Lower Carbonate Sequence KT-II.

2. During the period of the method's implementation, 8 thousand tons of additional oil were produced, which confirms the high potential of unsteady-state waterflooding with minimal operating costs.

3. The optimal regime is the ratio:

– 10–15 days of shut-in

– 3 days of injection.

This regime ensures maximum engagement of matrix reserves

4. Unsteady-state waterflooding makes it possible to reduce the water cut of produced fluids and increase the current oil recovery factor due to oil crossflow from the matrix to the fractures and improved sweep efficiency.

5. The most pronounced results are observed in wells that have penetrated zones of increased fracturing, which confirms the feasibility of using the method specifically in fractured reservoirs.

6. Cyclic waterflooding is recommended for use as a regular technological measure for 3–4 months per year, which provides a production increase in the short term and an increase in the final oil recovery factor (ORF) in the long term.

7. Considering the low efficiency of the current pressure maintenance system and the complex fractured structure of the reservoir, unsteady-state waterflooding is one of the most economical and productive methods for improving the efficiency of field development.

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