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Review and applicability assessment of acid treatment methods for bottomhole formation zones of carbonate complex reservoirs of oil and gas fields

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Abstract. The majority of the world and Russian Federation oil deposits are confined to complex carbonate reservoirs. Most carbonate reservoirs feature a complex geological and geophysical structure, the presence of high-capacity caverns, cracks, and pores, high-viscosity oils, as well as hard-to-recover reserves. To control development parameters in such challenging conditions and fulfill oil and gas production targets it is required to use modern enhanced oil recovery technologies. One of the most widely used methods is well acidizing to restore formation permeability. Today, global oil production employs various methods of acid treatment, which differ in their production technology, dependence on the lithological and mineralogical composition of the reservoir, duration, their effect, etc. Each of the methods used has both advantages and disadvantages, which sometimes makes it difficult for oil specialists to choose the right technology for treating the bottomhole formation zone. The present work discusses domestic and international experience in acid treatment of carbonate reservoir wells, in order to identify the advantages and disadvantages of the methods used.

Keywords: bottomhole formation zone treatment, fracturing, cavernosity, carbonate reservoir, flow rate, productivity coefficient, injectivity index

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Обзор и оценка применимости методик кислотных обработок призабойных зон карбонатных сложнопостроенных коллекторов нефтяных и газовых месторождений

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Резюме. Основная доля месторождений мира и Российской Федерации приурочена к сложнопостроенным карбонатным коллекторам. Большинство месторождений карбонатных коллекторов характеризуется сложным геолого-геофизическим строением, наличием в составе резервуара высокоемких каверн, трещин и пор, нефтей повышенной вязкости, а также трудноизвлекаемостью запасов. Для обеспечения контроля параметров разработки в столь сложных условиях и выполнения поставленных планов по добыче нефти и газа требуется применение современных технологий увеличения нефтеотдачи. Одним из наиболее применяемых мероприятий такого рода является кислотная обработка скважин с целью восстановления проницаемости пласта. На сегодняшний день в мировой нефтедобыче существуют различные способы кислотного воздействия, которые отличаются между собой технологией производства, зависимостью от литолого-минералогического состава коллектора, длительностью, эффектом воздействия и так далее. Каждый из применяемых методов обладает своими как положительными, так и отрицательными сторонами, что делает порой затруднительным для специалистов-нефтяников вопрос выбора технологии воздействия на призабойную зону пласта. В представленной работе приведен отечественный и мировой опыт проведения кислотных обработок скважин карбонатных коллекторов с целью выявления положительных и отрицательных сторон применяемых методик.

***Ключевые слова*:** обработка призабойной зоны пласта, трещиноватость, кавернозность, карбонатный коллектор, дебит, коэффициент продуктивности, коэффициент приемистости

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Introduction

During the operation of the deposit, there are often processes that lead to a gradual decrease in the permeability of the bottomhole formation zone. The main indicators used to evaluate the efficiency of wells are their flow rate, injectivity (in the case of using injection wells), productivity coefficient and the value of the oil recovery factor [1]. It is the latter factor that is the most important indicator of field development, since its value affects the production parameters, the selection of well intervention techniques to maintain the base production and provide incremental ultimate recovery of hydrocarbon. The most important property of a productive formation reservoir is its permeability. Permeability is the ability of a rock to allow a fluid (water, oil, gas) to go through it [2]. However, long-term operation of wells leads to damage of the porosity and permeability properties of the bottomhole formation zone of the reservoir, which leads to plugging of reservoir pores, formation of poorly soluble and insoluble compounds that negatively affects the fulfillment of schedule for oil and gas production and injecting a working agent into the formation in production and injection wells. The most common causes of deterioration of the reservoir properties of the bottomhole formation zone are the following:

– drilling fluid penetration during drilling in productive formation or penetration of cement slurry during cementing of casing and production strings;

– liquid penetration during technological flushing or penetration of products of technical and killing fluids into the formation;

– closing of perforation channels by various deposits and sediments;

– poor-quality performance of secondary formation drilling (perforation), well development and repair work;

– precipitation of paraffins, heavy oil sediments and inorganic salts in the productive formation;

– insufficient degree of water treatment (in case of using injection wells)[1].

All of the above causes lead to a decrease in well productivity and the formation of a skin factor, a hydrodynamic indicator that characterizes the occurrence of additional filtration resistance in the bottomhole formation zone and is described by the following expression[2]:

$$S = \left(\frac{k}{k_s} - 1\right)\ln\left(\frac{r_s}{r_c}\right), \quad (1)$$

where r_s – radius of the contaminated area, m; r_c – well radius, m.

The skin factor is most often formed during the secondary drilling in productive formation associated with perforation work. Since torpedo and cumulative perforation are currently the main methods of drilling in the formation, it is not always possible to obtain clean perforation channels to create an effective formation-to-well connectivity due to damage of the string cementation, sealing the walls of the perforation channels, which leads to the formation of a perforation skin factor, described by the expression [3]:

$$S_2 = S_{2f} + S_{sf} + S_V, \quad (2)$$

where S_{2f} – the skin factor, caused by phase effects; S_{sf} – the skin factor caused by wellbore perforation (dominates at zero phase shift); S_V – the skin factor caused by the vertical intrusion effect.

Currently, a very significant problem in the system of oil and gas field development is the decline in flow rate of production wells and injectivity of injection wells, since most fields in the Russian Federation, characterized by a decrease in oil and gas production, are at a late stage of development. The flow rate depends on a variety of geological and technological factors, including changes in the properties of bottomhole formation zone and physical and chemical properties of formation fluids, the dynamics of changes in formation pressure, a decrease in the pressure on the productive formation, draw-down pressure (most often at pressure above saturation pressure), a change in the value of the reduced well radius, etc. The flow rate of a production horizontal well is determined using the standard and well-known Darcy–Weisbach equation [4]:

[1] Telkov V.P., Lambin D.N. *Well productivity management: textbook.* Moscow: Gubkin Russian State University of Oil and Gas (NRU); 2019, 74 p.

[2] Nasyrov A.M., Borkhovich S.Yu., Bardanova O.N. *Development and killing of oil wells: textbook.* Moscow – Vologda: Infra-Engineering; 2022, 264 p.

$$Q = \frac{kh(\bar{P}_r - P_{wf})}{18{,}41 \times \mu_0 \times B_0 \times \left[\ln\left(\frac{r_e}{r_w}\right) - 0{,}75 + S\right]}, \quad (3)$$

where Q – horizontal well flow rate, m^3/day; K – permeability, μm2; h – net pay thickness of the formation, m; $\bar{P}_r$ – formation pressure, MPa; P_{wf} – bottomhole pressure, MPa; μ_0 – oil viscosity, MPa×s; B_0 – a formation volume factor, unit fraction; r_e – drainage radius, m; r_w – well radius, m; S – a skin factor.

To control well performance as part of the technological process of oil and gas field development and operation, enhanced oil recovery technologies are used, which are required to increase the oil recovery factor. There are many methods of enhancing oil recovery used in practice (hydraulic fracturing, squeeze cementing, additional perforation, thermal steam and steam cyclic treatment, vibrowave impact, etc.). However, the main method used to restore the permeability of the bottomhole formation zone is well acidizing. This is the most widespread and widely used method of stimulation of production and injection wells [5, 6]. The essence of technology is the reaction of aqueous acid solution with matrix minerals and newly formed secondary solid minerals that plug the perforation interval zones and the bottomhole formation zone itself [7]. The main types of acids used for the carbonate reservoir treatment are given in Table 1.

A brief historical overview of the acid treatment use

The first use of acid well treatments for wells was made in the USA in 1895 at wells near Lima, Ohio. The first application of acid composition was similar to the modern description of the technological process of exposure, which was the use of hydrochloric acid to dissolve limestone, presumably followed by cleaning out the well with water [8]. In Russia, the mass implementation of hydrochloric acid treatments was started in the oil fields of Bashkiria and Tatarstan in 1935 [9]. In 1933, Jesse Russell Wilson proposed the use of an acid combination, namely the use of both hydrochloric acid and hydrofluoric acid. The reason for this was that the early direct injection of hydrofluoric acid into the produc-

Table 1. Main types of acid treatment methods used for production wells[3]
Таблица 1. Основные типы применяемых способов кислотной обработки эксплуатационных скважин[3]

Types of hydrochloric acid treatment	Range of application
Hydrochloric bath	To remove the mud cake from the face
Hydrochloric acid treatment under pressure	Penetrating treatments of the bottomhole formation zone to create deeply penetrating channels
Mud acid treatment	To dissolve shale interlayers. Prohibited for carrying out in a carbonate reservoir
Foam acid treatment	To slow down reactions by 4–5 times (thereby increasing the penetration depth of the acid solution)
Thermal acid treatment	Used in dense carbonate rocks to accelerate the chemical reaction
Acid-oil emulsion treatment	To increase the depth of penetration into the bottomhole formation zone
Interval treatment	To increase the inflow of individual interlayer and align the injectivity profile and inflow profile
Polymer acid treatment	Increasing the flow rate of highly water cutting wells
Acid tunneling	Creating a wide tunnel. Increasing the inflow area by creating additional channels
Directed treatment	Redistribution of the acid stream based on the stream thickness

[3] Bitner A.K., Ayupov R.Sh., Kvesko N.G., Bezverkhaya E.V. *Productivity management of oil and gas wells and methods of enhancing oil recovery: textbook.* Krasnoyarsk: Siberian Federal University; 2025, 344 p.

tive formation led to plugging of formation pores with chemical reaction products, the formation of silicon tetrafluoride in the reservoir, which led to swelling of the clays of the sandstone reservoir [10]. Thus, the use of hydrochloric acid treatment for wells was justified to prevent the formation of insoluble compounds. This made it possible to prevent gelling materials from getting into the wellbore [11]. The author managed to propose a technology that made it possible to create a chemical reaction based on the interaction of hydrofluoric acid inside the well and the productive formation when it is mixed with a hydrochloric acid solution.

Since 1947, acid treatment has been practiced in the Baku oil fields, where there are terrigenous layers. Then, in the 1950s, modernization was carried out and recommendations were given on the use of an 8–15 % hydrochloric acid solution for well treatment. The kinetics of reactions of hydrochloric acid with carbonate minerals, which are represented by quartzite, dolomite and calcium sulfate, were investigated qualitatively. The effect of temperature and pressure on the reaction rate, etc., was studied. Technologies of thermal acid treatment have been developed. B.M. Suchkov made a huge and invaluable contribution to the development of acid treatment technologies for wells. Under his leadership acid treatments of carbonate and terrigenous reservoirs were performed. Currently, acid treatment of the bottomhole formation zone has reached a fundamentally new level. This is facilitated by the modernization of acid compositions and the improvement of well surveying methods before treatment. An example is the use of modern methods of production logging tests in wells such as temperature logging, noise logging, flowmetry to identify the working intervals of wells, determine the nature of the volume and composition of the inflow coming from the well. According to the results of the study, the most suitable intervals are selected for carrying out hydrochloric acid treatments and enhancing oil recovery [12]. Complex approaches are used for carrying out treatments due to the high degree of formation contamination, the presence of heavy oil sediments and inorganic salts, which include applying various types of acid compositions and techniques. Fundamentally new technologies for exposure to the productive formation (for example, acid tunneling) are being created, which make it possible to increase the effect of treatment and restoration of permeability under any operating conditions of wells.

An overview of the application of acid treatments for wells of carbonate reservoir deposits

The main purpose of hydrochloric acid treatments is to create highly permeable wormhole channels for communication between the productive formation and the well. A wormhole is a narrow or cavernous channel that forms in a productive carbonate reservoir [13, 14]. During the impact on the formation, the acid penetrates several meters within the carbonate reservoir. In conditions of this type of reservoir, a treatment design is carried out, which most often begins with the selection of candidate wells for well intervention techniques. A systematic selection of the proposed injection scheme is: alternate stages of injection of a solution of both acid and flow diverting compounds are performed. Further, preliminary and subsequent washing is carried out [15–18]. Since the composition of carbonate minerals is mainly represented by limestones and dolomites, it is advisable to use hydrochloric acid treatments for wells, as the minerals forming the carbonate reservoir react with hydrochloric acid very well and are perfectly soluble in water [19, 20]. So, in Robert Schechter and John Gidley's work [21], a model of hydrochloric acid dissolution of rock carbonate minerals is shown. In the experiment with a rotating disk, a pre-exponential factor was determined, the activation energy of which is equal at a temperature of 15.6–1.25 °C with a pressure value equal to 55 bar. To carry out mathematical calculations, a model of the created multicomponent diffusion of the applied chemical agents and products of the resulting chemical reaction was used, taking into account the emerging electrostatic forces. The constants of the created chemical reaction were determined using the following equation:

$$-r_{HCl} = E_f \times C_{HCl}^{m},\ E_f = E_f^{0} \times \exp\left(-\frac{\Delta E}{RT}\right). \quad (4)$$

It was found that at temperatures above 0 °C, the chemical reaction rate of carbonate minerals dissolution is limited by the processes of acid transportation to the surface of the chemical reaction being created, since for carbonate reservoirs at temperatures above 50 °C, the rock dissolution is limited by the processes of reaction kinetics. The characteristics of the dissolution reaction of carbonate minerals with hydrochloric acid are given in Table 2.

As mentioned earlier, the main purpose of acidizing of a productive carbonate reservoir is to create highly permeable wormhole channels for communicating the productive formation with the well [22, 23]. Wormholes in a carbonate reservoir have different sizes and can extend over distances from several to tens of meters, creating channels with high permeability values. In Sherman Putnam's work [24], experiments were conducted on the direct injection of hydrochloric acid into the core cavity of the rock, which is a direct confirmation of the use of hydrochloric acid solution for creating highly permeable narrow or cavernous channels. The model presented in Michael J. Economides's work [25] describes a process based on the fact that in order to estimate the volume of acid directed to create a wormhole at a certain distance, it is necessary to calculate how much of the rock under study is dissolved in the injected working agent. The wormhole penetration depth itself was determined by using the following expression:

$$r_{wh} = \sqrt{r_w^2 + \frac{V}{PV_{bt} \times \pi \times K_п \times h}}, \quad (5)$$

where r_{wh} – wormhole propagation radius, m; r_w – well radius, m; V – volume of injected acid, m^3; PV_{bt} – pore volume of acid composition before wormhole formation, unit fraction; $K_п$ – porosity, unit fraction; h – approximate thickness of the treatment interval.

The authors of [26, 27] proposed a method for determining the wormhole created in a productive carbonate reservoir using the technique of hydrodynamic modelling of a productive reservoir. The method of hydrodynamic modeling was used to fix the fluid flow to the created filtration channels of a given geometry. The results of the conducted research were recorded by obtaining the following expression:

$$V_{tip} = \frac{Q}{K_п \times h \times \sqrt{\pi \times m_{wh}}}\left[\frac{1-\alpha_z}{\sqrt{d_{e-wh} \times r_{wh}}} + \frac{\alpha_z}{d_{e-wh}}\right], \quad (6)$$

where Q – consumption of acid composition, m^3/s; m_{wh} – the number of wormholes in the plane orthogonal to the wellbore, units; α_z – the coefficient characterizing the wormhole distribution density along the wellbore, unit fraction; d_{e-wh} – effective diameter of the wormhole system, m.

The development of highly permeable wormholes is most often due to the intensive development of large-sized pore formation processes. In situ productive formation, the pore space of the reservoir contains pores of various sizes and shapes. For example, Robert S. Schechter's work [28] describes an attempt to perform a model of changes in the structure of the pore space of a rock during acidizing of a productive formation. So, based on the created pore distribution model (indicated in the work by the letter L) and the value of the cross-sectional area (indicated by the letter A), the medium of capillary tubes is distributed randomly in the volume of the productive rock. The determination of the pore velocity was considered based on the problem of convection diffusion of an active mixture in a pipe of arbitrary cross-section.

Table 2. Characteristics of the dissolution reaction of carbonate minerals with hydrochloric acid
Таблица 2. Характеристики реакции растворения карбонатных минералов соляной кислотой

Mineral	m	$E_f^0\left(\frac{\text{kg} \times \text{mol HCl}}{\text{m}^2 \times \text{s}\left(\frac{\text{kg} \times \text{mol HCl}}{\text{m}^3}\right)}\right)$	$\frac{\Delta E}{R}\ (K)$
Calcite	0,63	$7{,}291\times10^{7}$	$7{,}55\times10^{3}$
Dolomite	0,314–0,618	$9{,}4\times10^{11-3m}$	$11{,}32\times10^{3}$

On the surface of the pipe, the dissolution reaction of a carbonate mineral takes place. The model is described by the following equations:

$$\bar{C} = \begin{cases} c\left(x,\ t - \frac{z}{\bar{v}}\right)\exp\left(-\frac{\alpha E_f \Gamma}{A\bar{v}} z\right) \\ 0 \end{cases},\ t > \frac{z}{\bar{v}},\ t < \frac{z}{\bar{v}}, \quad (7)$$

$$\psi = C(x,\ t)\,\frac{\gamma A \bar{v}}{\rho_s}\left(1 - \exp\left(-\frac{\alpha E_f}{A\bar{v}}\right)\right),\ \alpha = \frac{1}{\Gamma\bar{C}}\int_{\Gamma}^{0} C ds, \quad (8)$$

where γ – dissolution power; E_f – reaction constant; ρ_S – rock density; Γ – perimeter of the pipe cross-section. If there is an infinite pore reaction rate for a circular section, then the determination of the rate is described by applying the expression:

$$\Psi = FXA^2\left(1 - \exp\left(-\frac{18{,}1 \times D}{FA^2}\right)\right),\ F = -\frac{1}{u\bar{L}}\frac{\partial \rho}{\partial z}, \quad (9)$$

where z – axial coordinate of the pipe; $\bar{v}$ – average fluid flow velocity; X – dissolution power of the acid; D – diffusion factor.

The work of the authors [29] is devoted to the creation of a mechanistic model for the growth of a reservoir wormhole in a model of capillary tubes with permeable walls for a reaction limited by the transport of the acid used for treatment, without taking into account the phenomenon of wormhole intergrowth. Based on the mass balance in the wormhole under study, a kinetic equation is derived, where the length of the created wormhole is indicated by the letter l, and the radius of the wormhole is indicated by the letter r. The final expression looks like this:

$$\frac{dl}{dt} = \frac{X}{\rho} \times (uC)_{tip},\ \frac{dr}{dt} = \frac{X}{\rho}\left(vC - D\frac{\partial C}{\partial r}\right)_{wall}, \quad (10)$$

where X – dissolution power of the acid; ρ – mineral density; v – velocity components along and across the wormhole, which are taken from the analytical solution for a pipe with permeable walls; D – diffusion factor; C – the acid concentration determined from solving the convection-diffusion equation with specified values of velocity fields; the *tip* and *wall* indices refer to the tip of the wormhole and its wall.

The above-listed models consider the created highly permeable wormhole channels of a carbonate reservoir. In the conditions of a productive carbonate reservoir, both hydrochloric acid solutions and various types of diverters used in practice (which most often include reducing the reaction rate of hydrochloric acid with rock) are used to increase the oil influx. Solvents are also applied to destroy product residues of drilling fluids, killing fluids and heavy oil sediments. Thus, the authors N.I. Khisamutdinov and A.N. Astakhova [30] note the success of the carbonate reservoir of hydrochloric acid treatments by covering the impact on the bottomhole formation zone, which consists of the following components:

– the values of the carbonate component in the formation section of the bottomhole formation zone;

– the depth of acid penetration into the formation;

– uniformity of the injectivity profile and the inflow profile;

– the dissolution structures and the created mechanism of dissolution [34].

The dissolution structure of the rock is noted as a result of the created chemical reaction, it has multilateral subsystems that are distributed into surface dissolution, created conical wormholes, dominant wormholes, branched wormholes and uneven dissolution in volume, taking into account the heterogeneity of the distribution of the carbonate component vertically. For example, in his works [31–33], D.A. Martyushev considers the effect of the injection rate in a carbonate reservoir. Studies have confirmed this dependence: with an increase in the carbonate content of the rock, the optimal rate of injection of the acid composition decreases. When modeling acid treatments using the example of deposits in the Perm Region, the formation of through high-conductive filtration channels is observed, which properly ensure an increase in reservoir permeability. At extremely low rates of acid composition injection, the dissolution process of the carbonate rock is accompanied by an approximate dissolution of the face of the core material sample.

Recently, the success of acid treatments in productive carbonate reservoirs has been determined by the use of diverters. The implementation of acid treatment diverters is due to situations where it is necessary to apply large volumes of acid compositions used for the treatment for the bottomhole formation zone of the carbonate reservoir with regard to the need for high reservoir stimulation. This approach is most applicable in deposits that are confined to low-temperature dolomite reservoirs. Examples of such deposits can be the Yurubcheno-Tokhomskoye, Kuyumbinskoye, or carbonate reservoir deposits of the Volga-Ural and Timan-Pechora oil and gas provinces [34–37]. Let us consider the most commonly used types of diverters.

Viscoelastic diverting acid (VDA) is a self-diverting acid based on the use of viscoelastic surfactants, used most often for productive carbonate reservoirs. Long-term experiments and the results of the implementation of this type of diverter within the Russian Federation show that when using it, there is an increase in well productivity in the range of 30 and up to 300 %, depending on the degree and stage of field development and the technical condition of the well under study.

OilSEEKER is one of the types of diverters used, which is a polymer-free plugging agent based on a viscoelastic composition of surfactants. It is actively used for stimulation with high water cut of the produced products, since its application is based on the technology of selective plugging of water-saturated zones, allowing the acid used to affect zones with a high degree of saturation of the deposit. The use of this type of diverter makes it possible to reduce the amount of water cut of products by several times, which significantly increases the flow rate of producing wells of carbonate reservoirs. OilSEEKER is most relevant for deposits of carbonate reservoirs with the presence of zones of increased fracturing and cavernosity, which makes it possible to maintain high values of reservoir porosity and permeability properties, including in cracks and cavities.

Selective acid treatment is used to treat the carbonate reservoir [38–41]. The essence of this technology is to divide the formation into intervals and selectively treat each interval separately with acid. Selective treatment is most applicable in a carbonate reservoir to increase the communication of the formation with the well. Colmatant is formed in interlayers when it is saturated with formation water and subsequently dissolves in oil. Also, this method of hydrochloric acid treatment is called both intraformational and interval method. Packers, specialized chemical insulation substances, as well as thermal acid treatments are used to carry out interval treatment for the target interval of the formation under study. The method of high-volume selective acid treatment is most often used [42]. Its essence lies in injecting into a carbonate reservoir into a well, an acid solution fringe with a volume of 1.5–3 m^3 per 1 m of oil or a gas-saturated interval and a non-linearly viscous diverter fluid before and after injection the acid composition fringe. The method is most applicable for a complex carbonate reservoir, which allows increasing the value of the productivity coefficient, the flow rate of production wells and the injectivity index of the injection well, including in cracks and high-capacity cavities.

When acidizing is carried out, various kinds of geological heterogeneities of the productive formation play a significant role. These are zones of increased fracturing and cavernosity, as well as micro-, macro-cracks, micro-caverns, pores and leaching zones. Since it is important to know the main geological inhomogeneities when designing a treatment, the choice of using the method of acidizing of the formation and the amount of reserves recovery on the degree of their spread in the productive reservoir. In such cases, the inflow of oil and gas is observed in highly permeable formations, while the remaining adjacent formations remain without effective impact on the bottomhole formation zone. The most complete application of acidizing methods for a carbonate reservoir is shown in the works [43–63], where the issues of acidizing of a productive carbonate reservoir are considered in detail. The issues of selecting the acidizing technique for the carbonate reservoir, the mechanisms of acid treatment, and the geological and technological conditions of the techniques are described.

A typical application of acid treatment was considered in our previous work [62], where, using the example of the carbonate reservoir of the Verkhnechonskoye field, the applicability of the treatment for the bottom-hole formation zone as a way to increase well pro-

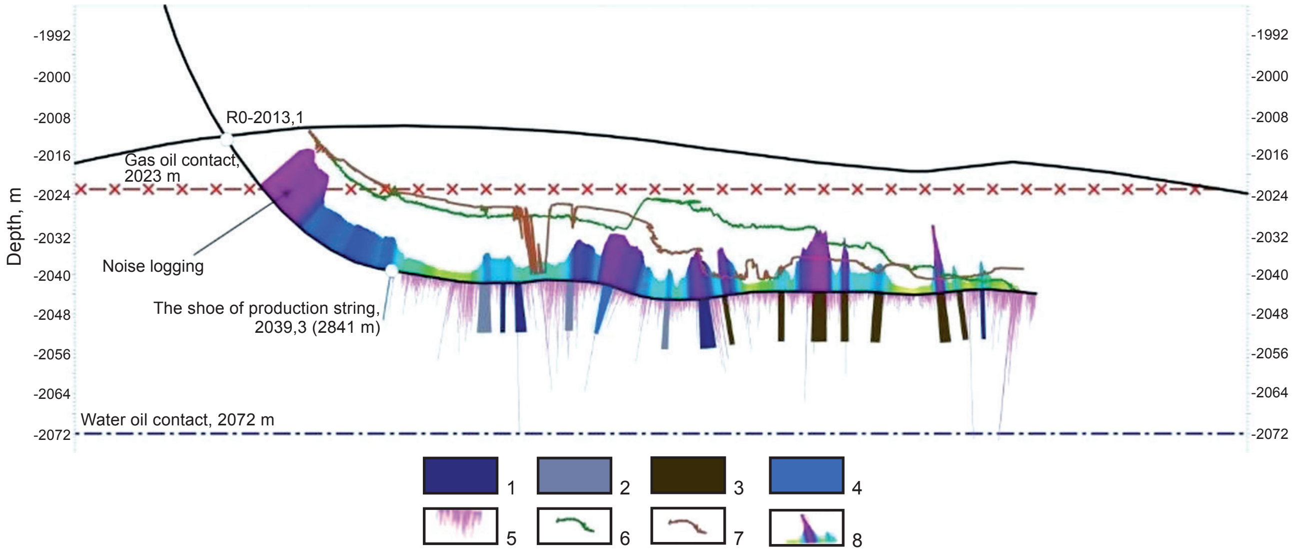

Fig. 1. Acidizing diagram for a production well based on production logging data (Yurubcheno-Tokhomskoye field):
1 – oil + water; 2 – water + oil; 3 – oil; 4 – water;
5 – drilling fluid loss rate; 6 – temperature logging; 7 – mineralization; 8 – noise logging
Рис. 1. Диаграмма проведения кислотной обработки добывающей скважины с опорой на данные промыслово-геофизических исследований (Юрубчено-Тохомское месторождение):
1 – нефть + вода; 2 – вода + нефть; 3 – нефть; 4 – вода;
5 – интенсивность поглощения бурового раствора; 6 – термометрия; 7 – минерализация; 8 – шумометрия

Table 3. Study intervals of production wells of the Yurubcheno-Tokhomskoye field using production geophysical research methods before acid tunneling
Таблица 3. Интервалы исследования добывающих скважин Юрубчено-Тохомского месторождения методами промыслово-геофизических исследований перед кислотным туннелированием

Well number	Caprock, m	Bottom, m	Effective thickness, m	Inflow composition
S-678	2370	2381б6	3,8	Oil + water + gas
S-235	2408,7	2412,5	15,1	Water + oil
S-989	2380	2386,6	7,4	Gas + oil + water
S-567	2400,1	2407,9	12,1	Oil + water + gas
S-976	2483,6	2495,2	10,9	Oil + water + gas
S-456	2495,8	2507,8	9,7	Water + oil
S-899	2512	2534	13,2	Gas + oil + water
S-457	2617	2623	6,6	Oil+ water + gas
S-324	2100	2112	10,5	Water + oil
S-333	2598,1	2601,9	8,4	Gas + oil + water
S-777	2617	2632	6,9	Water + oil
S-981	2597	2644	11,2	Oil + water + gas
S-343	2623	2651	12,9	Water + oil
S-789	2650	2680	13	Oil + water + gas

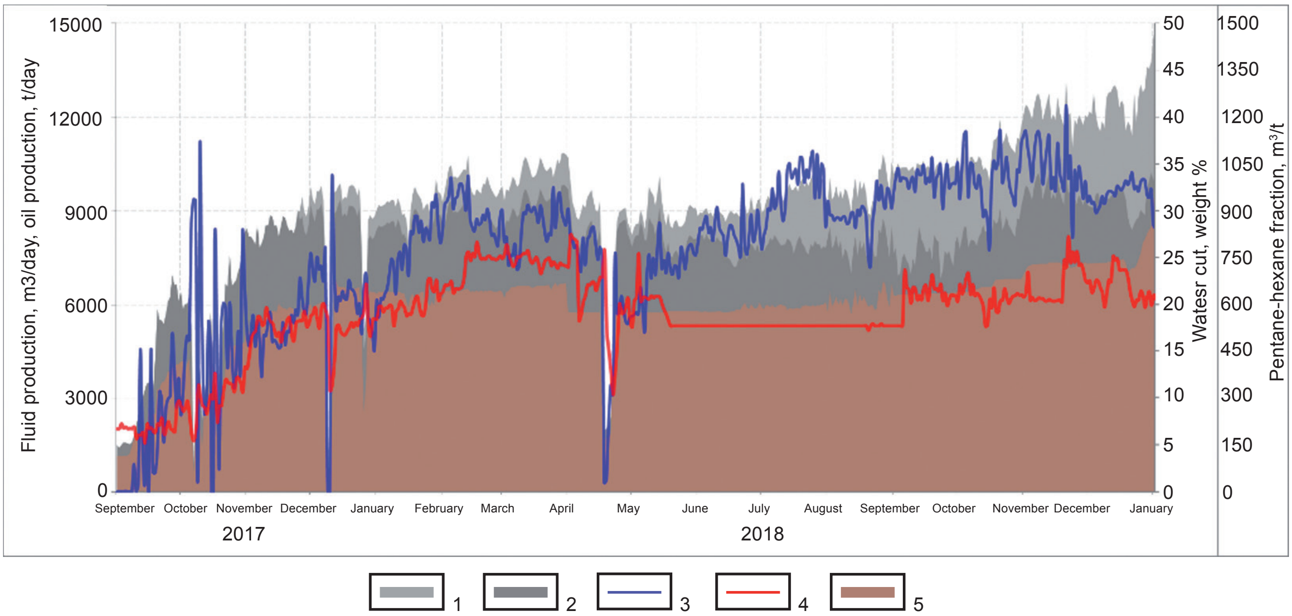

Fig. 2. Dynamics of production well operation after hydrochloric acid treatment:
1 – liquid; 2 – liquid (fountain); 3 – water cutting; 4 – gas factor; 5 – oil
Рис. 2. Динамика работы добывающей скважины после соляно-кислотной обработки:
1 – жидкость; 2 – жидкость (фонтан); 3 – обводненность; 4 – газовый фактор; 5 – нефть

ductivity was observed. The deposits of the Lena-Tunguskaya province of the Nepsko-Botuobinskaya oil and gas area are characterized by their association with the fractured cavernous and fractured porous reservoir type of the Vendian-Cambrian carbonate complex. The methods of standard acid treatment and a hydrochloric acid bath restore the permeability of a complex reservoir by creating wormhole channels for communicating the productive formation with the well, which makes it possible to fulfill the set plans for development indicators and provide incremental ultimate recovery due to well intervention techniques. One of the innovative methods is the acid tunneling method (chemically enhanced by drilling), which is an effective technology for restoring the permeability of the bottomhole formation zone. This technology was proposed by John Misselbrook. The essence of the method is running into the well by means of coiled tubing technologies (coil tubing) of an arrangement that contains logging tools for conducting geophysical surveys of wells and geonavigation to control the trajectory of the tunnel direction. The process of acid tunneling is the creation of new wellbores-contacts with productive rock, which makes it possible to increase permeability both in the bottomhole formation zone and in the remote formation zone. The tunnels formed during acidizing remain uncased, which further improves the formation-to-well connectivity. This method is unique due to the effective increase in the flow rate of production wells and the injectivity of injection wells. The running using coiled tubing technologies allows not only to increase the effect of the technique, but also to reduce the disadvantages that arise during acid treatment by means of a wash-jetting shoe and the running of tubing associated with water coning to the bottomhole (to increase the water cut of products), an increase in the risk of accidents during pipe running and a decrease in the ability to obtain sufficiently clean pore channels in the bottomhole zone. All this makes it possible to apply this technique for the well development and stimulation. The most complete application of the technology is considered in the work [63]. Thus, the acid tunneling method is applied successfully to increase the permeability of a complex carbonate reservoir. To choose the acidizing technique, the interval is determined, which is selected for the carbonate reservoir using production logging tests. An interpretive table for geophysical well logging is shown in Fig. 1. The study intervals are shown in Table 3.

The result of the application of acid tunneling makes it possible to increase the flow rate of production wells by several times, which confirms the high efficiency of the technology for production stimulation of oil and gas. The dynamics of daily oil and gas production using the example of the well in the Yurubcheno-Tokhomskoye field is shown in Fig. 2.

Above, we discussed the specifics of using the hydrochloric acid treatment method for production stimulation in carbonate reservoirs, and now we should move on to the conclusion.

Conclusion

In the presented work, the authors reviewed the methods of acid treatments for carbonate reservoirs of oil and gas fields. It has been established that the effectiveness of a particular technology of exposure to a carbonate reservoir is influenced by the geological and technological conditions of treatment, the rate of acid solution injection, and the mineralogical and lithological composition of the productive reservoir, the operating parameters of oil and gas wells before shutting down for well inervention techniques, etc. To justify the effectiveness of the exposure, the mechanism of creating highly permeable wormholes in the carbonate reservoir, the treatment technology, as well as the necessary geological and technical difficulties of treatment for the productive reservoir should be taken into account. Compliance with these recommendations will allow companies-subsurface users to choose one or another technology of treatment for the bottomhole formation zone to maintain production, taking into account the necessary positive and negative features of the methodology.

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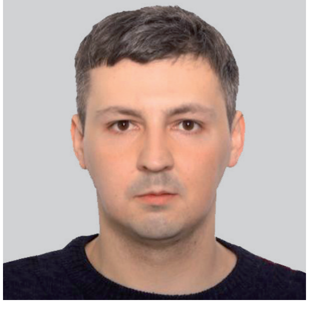

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