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The Method of Predicting Efficiency of the Matrix Acid Treatment of Carbonates

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Методика прогнозирования эффективности матричных кислотных обработок карбонатов

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Acidizing is one of the most common methods of influencing the borehole zone for stimulation in the international practice of developing hydrocarbon fields. Despite essential accumulated experience, subsoil users are facing reduced planned and actual production rates after this type of operations, which is due to both the deterioration of the resource base and ineffective solutions during their design. A scientific justification for design of acid treatments is required taking into account individual well conditions and a pre-evaluation of their effectiveness to reduce production and economic risks. This study presents a method for predicting results of acid stimulation on the formation based on the multivariate regression analysis and laboratory studies on rock samples. Its approbation was carried out using a carbonate production facility of an oil field in Perm Kray. The obtained statistical dependencies made it possible to accurately determine prospects of the planned geological and technical measures, give recommendations for adjustments to achieve the target indicators. The laboratory experiments resulted in identifying optimal technological parameters: the prospects of bulk acidizing with an exclusion of the acid exposure stage for the reaction. The integration of the mathematical and physical modeling results made it possible to select the required design of acid treatments in relation to the considered geological and physical conditions and estimate their expected efficiency. The developed technique can be used to rank candidate wells, form and adjust targeted programs for geological and technical measures for short and long term periods, and determine the stimulation technology. The described algorithm can be successfully replicated to other fields.

Ключевые слова:
кислотная обработка, кислотное воздействие, методы интенсификации притока, геолого-технические мероприятия, карбонатный коллектор, пустотное пространство, червоточина, кислотный состав, нефтяные месторождения, геолого-физические факторы, продолжительность выдержки, расход кислоты, скорость закачки, образцы керна, рентгеновская томография, фильтрационные эксперименты, комплексная методика, пошаговый регрессионный анализ.

В международной практике разработки месторождений углеводородного сырья одним из наиболее распространенных методов воздействия на призабойную зону пласта для интенсификации притока является кислотная обработка. Несмотря на значительный накопленный опыт, предприятия-недропользователи все чаще сталкиваются со снижением плановых и фактических приростов дебитов после данного рода мероприятий, что обусловлено как ухудшением состояния ресурсной базы, так и принятием ошибочных решений при их проектировании. Необходимо научное обоснование дизайна кислотных обработок с учетом индивидуальных условий скважин и предварительной оценкой их эффективности для снижения технологических и экономических рисков. В настоящем исследовании представлена методика прогнозирования результата кислотного воздействия на пласт на основе многофакторного регрессионного анализа и лабораторных исследований на образцах горной породы, проведена ее апробация на примере карбонатного эксплуатационного объекта нефтяного месторождения Пермского края. Полученные статистические зависимости позволили с высокой точностью определить потенциальную успешность запланированных геолого-технических мероприятий, дать рекомендации по их корректировке для достижения целевых показателей. В ходе лабораторных экспериментов выделены оптимальные технологические параметры воздействия: установлена перспективность многообъемных кислотных обработок при исключении этапа выдержки кислоты на реакцию. Комплексирование результатов математического и физического моделирования предоставило возможность выбрать необходимый дизайн кислотных обработок применительно к рассматриваемым геолого-физическим условиям и оценить их ожидаемую технологическую эффективность. Разработанная методика может использоваться для ранжирования скважин-кандидатов, формирования и корректировки адресных программ геолого-технических мероприятий на краткосрочный и долгосрочный периоды, определения технологии воздействия. Описанный алгоритм может успешно тиражироваться на другие месторождения.

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Introduction

More than 60 % of remaining recoverable oil reserves at the territory of Perm Kray belongs to carbonate deposits. In such conditions acidization is one of most common methods, which forms holes of various geometries and directions responsible for changing voids in rocks, thus, changing their permeability [1–9].

The first similar operation was carried out in 1895, when an American organization Ohio Oil Company injected hydrochloric acid into wells operating carbonate reservoirs, which resulted not only in an increase of the level of production of raw materials, but also in corrosive destruction of production strings [10]. Further experience of using the method dates back to 1931, which was facilitated by the discovery of the inhibiting properties of arsenic to reduce the activity of aqueous solutions of acids [11]. The main advantage of acidizing compared to other existing technologies (in particular, hydraulic fracturing) is a wider field of application at lower financial costs.

Despite many years of applications, oil producing enterprises are increasingly facing reduced planned and actual production rates after acid treatments of borehole zones with acid compositions, which is due to a combined influence of geological, physical and technological factors. Scientists and specialists refer conditions of the filtration processes to the first group of factors: composition and properties of reservoir rocks and fluids, reservoir pressure and temperature [12–17]. The second group includes the acid composition exposure time, the rate and pressure of the solution injection into the reservoir [18–23]. Geological characteristics are determined by the conditions of sedimentation during a deposit formation, therefore the options of regulating them are either limited or unavailable. In this regard, it is relevant to justify the optimal design of the acid treatment by taking into account individual properties of the near-wellbores and evaluating effectiveness of the treatment already at the design stage to reduce economic and technological risks.

Mostly, hydrodynamic simulators are used to predict results of geological and technical measures (GTM) [24]. They make it possible to evaluate the operations in conditions of well interference and consider reservoir geological structures. Nevertheless, as no special keywords are available, the modeling of borehole treatment (BHT) is based on *manual* changes in the skin-factor or reservoir connectivity, the range of which is set on the basis of the geological field analysis. While the accumulated oil production can deviate both in overestimation and underestimation, which in the future does not assist in deciding if this measure is worth implementing.

The use of the specific productivity index obtained on the basis of historical events in similar geological and physical conditions [25] is another common approach to evaluate effectiveness of acid treatments. This analytical method allows you to quickly calculate an increase of fluid flow rate, if an appropriate database is available, but its accuracy is low, since various factors accompanying the process are not sufficiently considered.

In addition, the above methods do not allow taking into account the technological parameters of acid treatments, including a type of working agent, which becomes possible by using methods of mathematical statistics and laboratory experiments on cores.

In this paper, we present the developed complex technique of predicting acidizing results of reservoirs using the multivariate regression analysis and laboratory studies of the rock samples (Fig. 1). The algorithm is evaluated by using carbonate production facilities of Perm Kray with multiple acidizing, both basic one and those combined with casing perforations.

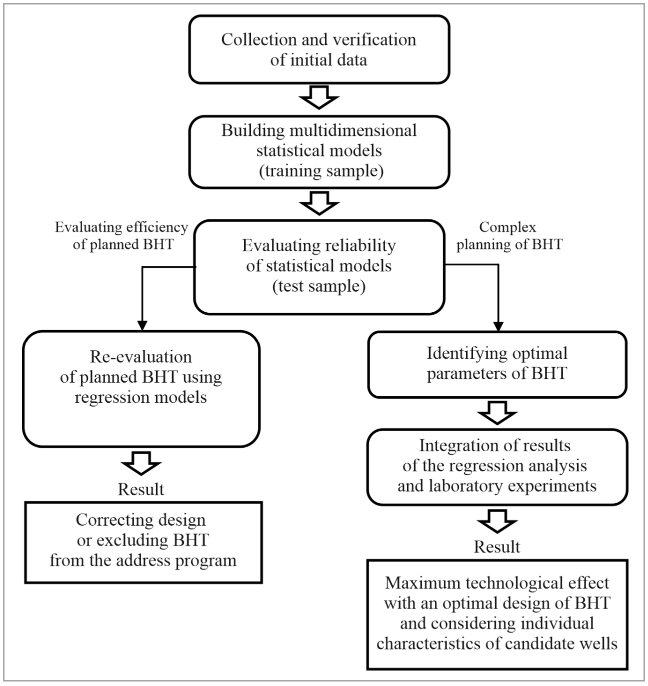

Fig. 1. Algorithm and application of the efficiency prediction method for BHT

Geological and Physical Characteristics of the Studied Facilities

The studied oil reservoir has a complex geological structure, accompanied by a strong heterogeneity along the section (the compartmentalization coefficient is 4.7 unit fractions, the net-to-gross ratio is 0.35 unit fractions) and rather low permeability ($21\cdot10^{-3}$ μm^2). The deposits are represented by fine-, medium- and coarse-crystalline limestones with smears of clay material; detrital-clotted and detrital-cloddy-clotted interlayers predominate. Cement of calcite, porous and regenerative types. The oil is light (density is 734 kg/m^3), low-viscosity (1.2 mPa·s), paraffinic (3.2 %), resinous (10.1 %) and sulphurous (0.6 %). The energy state of the reservoir is satisfactory: the current reservoir pressure is 16.7 MPa at the initial value 18.1 MPa and gas saturation pressure is 7.9 MPa.

The structure of the void space of a rock can determine the effectiveness of chemical treatments [26–30]. Thus, special studies of the core samples were carried out using X-ray tomography (Fig. 2). It was found that the reservoir void space has a porous-cavernous type, which restraints the implementation of acid treatments.

An increased content of dolomite and insoluble minerals in the rock composition can negatively affect the result of chemical actions, e.g. lead to clogging of voids with some reaction products [14, 26, 31]. As such, the component composition of the rock was investigated using the KM-04M carbon meter. To increase the reliability of the results, 20 experiments were carried out, according to their results, it was noted that the deposits are mainly represented by calcite or limestone (96.2 %), and the content of dolomite and insoluble minerals (quartz and argillite) is low 0.3 % and 3.5 %, respectively.

Developing Statistical Models to Predict Efficiency of Acidizing

To create statistical models, we considered operations taken with acid that stimulate exposed sublayers, that is a basic acid treatment (31 well operations) and its combination with re-perforation (25 well operations). In all cases, one working agent was used, i.e. an aqueous solution

Table 1

The correlation matrix of geological, physical and technology indicators influencing efficiency of BHT

Indicator	Δq	w	K_{bz}	K_{rzr}	P_r/P_{sat}	q_0	$P_{bp}/_{sat}$	q_{ac}	P_{inj}	v_{inj}
Δq	1.00	–0.33*	–0.33*	–0.30*	0.14	0.61*	-0.03	0.74*	-0.04	-0.23
w		1.00	-0.03	0.05	-0.03	-0.31*	-0.14	-0.26	0.03	0.13
K_{bz}			1.00	0.81*	0.02	-0.08	0.17	-0.15	0.03	-0.10
K_{rzr}				1.00	0.01	-0.12	0.21	-0.11	0.11	-0.06
P_r/P_{sat}					1.00	0.06	0.63*	0.15	0.48*	-0.24
q_0						1.00	-0.05	0.58*	-0.13	-0.16
P_{bp}/P_{sat}							1.00	-0.09	0.22	-0.12
q_{ac}								1.00	-0.04	0.04
P_{inj}									1.00	-0.25
v_{inj}										1.00

Note: * the statistically significant correlation.

of hydrochloric acid (14 %) with a corrosion inhibitor and other highly effective additives.

Geological, physical and technological indicators are involved, which theoretically can influence the result of acidizing: permeability of the borehole and remote zones of the reservoir (K_{bz} and K_{rzr}, μm^2); water cut (w, %); the ratio of reservoir and borehole pressures to oil saturation pressure (P_r/P_{sat} and P_{bp}/P_{sat}, unit fractions); specific oil production rate before well shut-in for workover (q_0, t/day·m)); specific acid consumption (q_{ac}, m^3/m); injection pressure (P_{inj}, MPa); injection rate (v_{inj}, m^3/h); exposure time per reaction (T_{et}, h). The specific increase in oil production after the event (Δq, t/(day·m)) was taken as an indicator of the operation effectiveness.

Initially, a full sample was considered without subdividing activities into acid treatments with and without re-perforation. The indicators were evaluated using Pearson's correlation coefficient r at significance level p equal to 0.05 (Table 1). The time of the acid exposure for the reaction is not included in the matrix due to the discreteness of the values (4–6 h).

There is a statistically significant influence of reservoir filtration characteristics and acid flow rate on the specific increase in oil production rate, and some of the studied elements are well correlated with each other. Based on this, by using the stepwise regression analysis [32–34], we built a multivariate model (1):

$$\Delta q^{M1} = 0{,}057 \cdot q_{ac} + 0{,}166 \cdot q_0 - 2{,}090 \cdot K_{bz} - \\ - 0{,}004 \cdot w + 0{,}313 \\ (r = 0{,}81;\ p < 0{,}05). \tag{1}$$

The comparison of model (Δq^M) and actual (Δq^a) values is given in Fig. 3, *a*. The average inaccuracy was 0,138 t/(day·m). When the actual specific increase in oil production rate is more than 1.0 t/(day·m), the correlation field is heterogeneous, which is probably caused by some misconsidered factors, in particular, the method of reservoir stimulation.

As such, by analogy, the regression equations were obtained for a basic acid treatment (2) and the treatment with re-perforation (3):

$$\Delta q^{M2} = 0{,}059 \cdot q_{ac} - 2{,}987 \cdot K_{bz} + 0{,}150 \cdot q_0 - \\ - 0{,}006 \cdot w - 0{,}025 \cdot v_{inj} + 0{,}544 \\ (r = 0{,}91;\ p < 0{,}05); \tag{2}$$

$$\Delta q^{M3} = 0{,}113 \cdot q_{ac} - 2{,}779 \cdot K_{rzr} - \\ -0{,}053 \cdot v_{inj} - 0{,}011 \cdot P_{inj} + 0{,}538 \\ (r = 0{,}72;\ p < 0{,}05). \tag{3}$$

The model and actual indicators correlate well with each other (r = 0.72–0.91), which can be seen in Fig. 3, *b*.

Taking into account the technology of the event made it possible to reduce the absolute inaccuracy to 0.114 t/(day·m), or by 17.4 % relative to the equation for a full sample of data (1), which indicates an increase in the prediction quality. More details on the algorithm for constructing computational multidimensional models can be found in [35].

Reliability Evaluation of the Regression Models and their Application to Determine Efficiency of Geological and Technical Measures

To assess the reliability of the developed statistical dependencies and their applications, additional geological and technical measures were involved, the so-called test sample: four wells each for a basic treatment and re-perforation followed by acid injection (Fig. 4, a).

The absolute increase in oil production after the treatment was determined by multiplying the model specific value of the efficiency indicator by the acid-treated oil-saturated reservoir thickness. The planned value of the increase in the oil production rate is understood as its value determined by analytical methods (through the specific productivity factor), the predicted value entails using regression equations (2) and (3).

The comparison of the results of the calculated and actual values of the increase in oil production after the acid treatments at the considered wells showed that the absolute measurement error varies from –0.9 to 0.3 t/day, the relative measurement error was from –12.5 to 6.8 % (the prediction accuracy was 87.5–93.2 %). The high convergence of the model and actual values of the technological efficiency indicator makes it possible to use the developed equations to assess prospects of acid stimulations in individual geological and physical conditions of wells.

The next step was to evaluate the effectiveness of acid treatments included in the targeted program of geological and technical measures with the use of statistical dependencies. In total, we considered 12 well operations at the facilities and their analogs. According to the results of the calculations, it was found that the success of the basic acid treatments was 75 %, and for those with re-perforation it was 87.5 % (Fig. 4, b).

To achieve the planned increase in oil production during the basic acidizing (well No. 2), it is recommended to consider the possibility of increasing the injected acid composition of well No. 9, re-perforation will be an ineffective measure, which is caused by the increased water cut (45.8 %) and permeability of the borehole zone (according to hydrodynamic studies, 325·10–3 μm^2), as a result of which the main volume of the acid composition will be filtered through the washed sublayers with no involvement of new areas in the development process. Refusal from ineffective measures at the design stage will reduce costs by an average of 2.5–2.9 million rubles for each well operation.

Laboratory Studies Using Rock Samples

The scientific justification of design is one of the most important issues in planning any geological and technical operations [36–40]. To determine the main technological

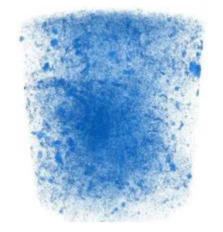

Fig. 2. Three-dimensional model of the core sample obtained using the X-ray tomography

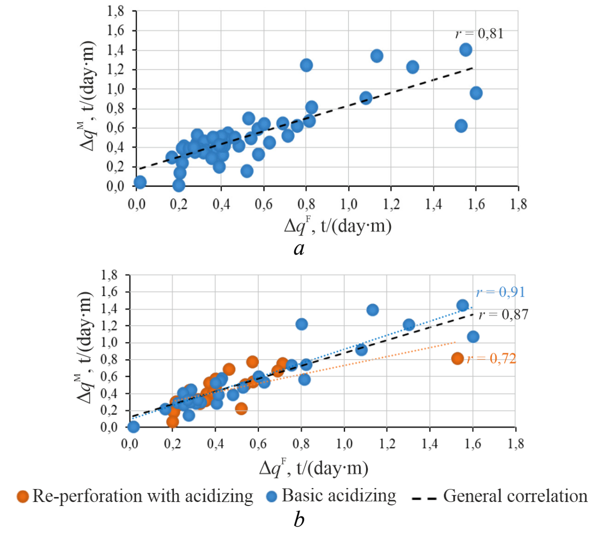

Fig. 3. Comparing model and actual values of the specific increase in the oil production rate: *a*) is a full sample; *b*) during sample grouping according to treatment types

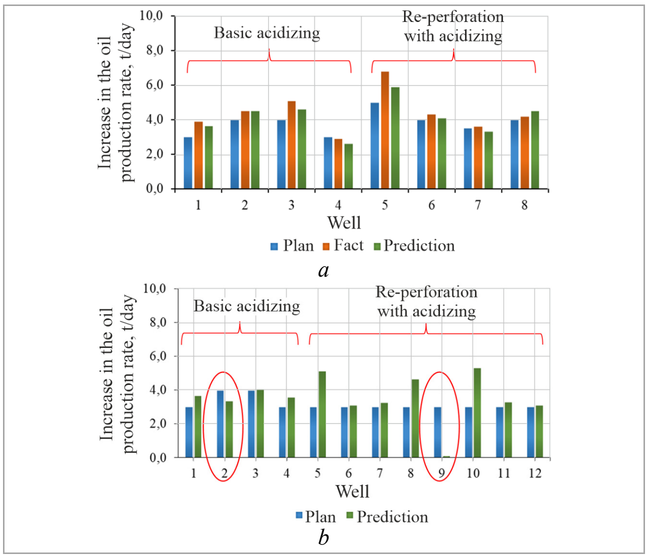

Fig. 4. A comparison of values of increase in the oil production rate after BHT: *a*) planned, actual, predicted values; *b*) planned and predicted values

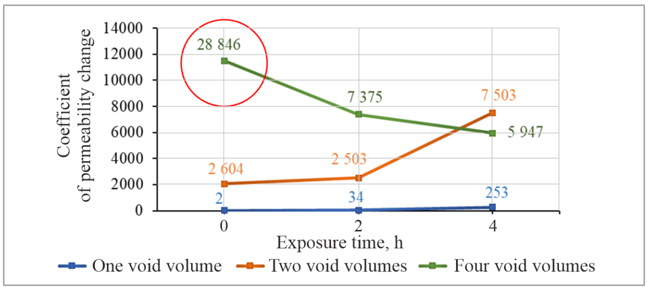

Fig. 5. Generalized results of filtration experiments using core samples

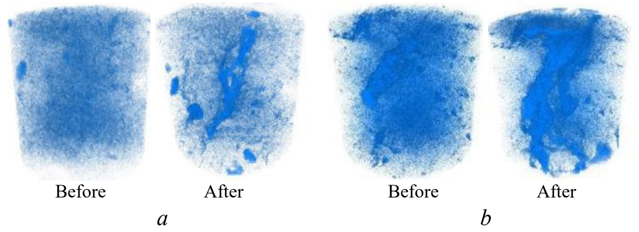

Fig. 6. 3D model of the sample related to acidizing: *a*) No. 1; *b*) No. 2

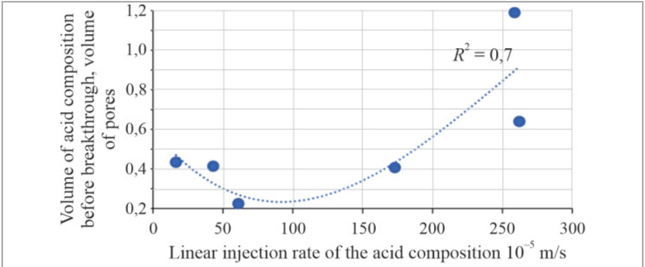

Fig. 7. Finding an optimal injection rate

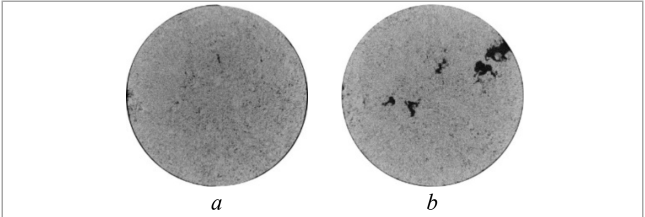

Fig. 8. Branching of the wormhole using an example of a cut of the core sample No.2: *a*) before acidizing; *b*) after acidizing

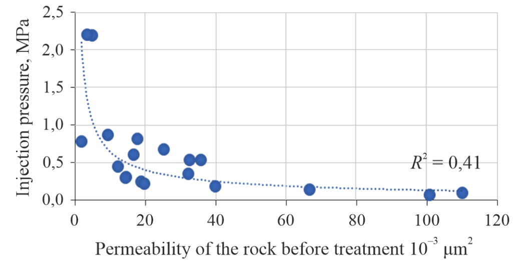

Fig. 9. Dependence of injection pressure on rock permeability

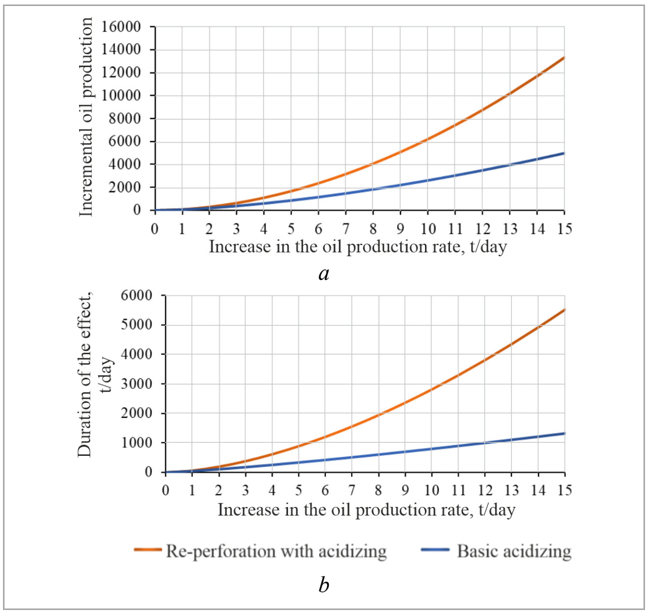

Fig. 10. Dependence on increase in the oil production rate after BHT: *a*) an incremental oil production; *b*) duration of effect

parameters of acid stimulation (the time of exposure in the reservoir per reaction, the volume and rate of injection of the working agent), filtration studies were carried out with the core [41–43]. High-pressure units AFS-300 and UIK-5VG were used for the experiments and included modeling of temperature and pressure conditions of the reservoir. We take the coefficient of permeability variations as an indicator of the operation effectiveness, it is the ratio of phase permeability as per the oil model after treatment (K_{o2}) to its initial value (K_{o1}). Nikon Metrology tomograph XT H 225 was used to estimate changes in the void space of the rock samples before and after acid exposures [44–46].

A total of 18 filtration experiments were performed with pumping 1, 2, 4 pore volumes of the acid composition and exposure per reaction 0; 2; 4 h. The generalized research results are presented in Fig. 5. According to the presented data, there is a tendency for the treatment efficiency increase depending on the consumption increase of the working agent. The maximum change of the rock permeability is observed when pumping four pore volumes of the acid composition without exposure per reaction. To transfer the results to the wells, it is assumed that one pore volume corresponds to an agent flow rate of 1 m^3 per 1 m of a reservoir thickness.

Two experiments were accompanied by X-ray tomography before and after exposure, which allows you to visualize changes in the structure of the rock void space. When two pore volumes of the acid composition were injected and held for 4 hours for reaction in sample No. 1, a wormhole was formed, which caused an increase in permeability by 386 times (Fig. 6, a). The increase of the void space volume according to the results of X-ray tomography was 484.7 mm^2 (26.5 %), porosity was 1.5 %. The coefficient of permeability change for sample No. 2, characterized by the presence of pronounced caverns, after injection of four pore volumes of acid and exposure for 4 h, was 5,947 fraction units. (Fig. 6, b). The volume of the void space changed from 673.1 to 1084.5 mm^2, the porosity coefficient changed from 3.6 to 5.8 %. The presence of caverns in the rock structure contributed to the directional movement of the acid and the formation of channels, however, in practice, filtration of the agent through the washed sections of the reservoir can lead to breakthroughs of reservoir water.

To estimate the optimal injection rate of the acid composition, the results of earlier experiments with the agent breakthrough were used [47]. During the experiments, we recorded the total volume of the injected acid and the maximum injection pressure until it appeared at the outlet end of the core sample. It was found that at low injection rates of acid solutions (up to 40·10–5 m/s), the exposure process is accompanied by a local dissolution of the rock, and the formation of a wormhole takes more time, which is consistent with the results of researchers [48]. In this case, the optimal linear injection rate of the acid composition was 93·10–5 m/s (Fig. 7).

The linear value of the acid injection rate is quite simply calculated into the volumetric value: to treat 1 m^2 of the borehole zone's surface, the composition flow rate on the well wall of 3.3 m^3/h will be required. Further pumping of the solution after the breakthrough is accompanied by the branching of the wormhole (Fig. 8). The required injection pressure is determined depending on the values of the rock permeability (Fig. 9).

The selected optimal technological parameters will increase the efficiency of acid treatment both at the stage of well development after drilling and stimulation of the inflow at the operating well stock.

Evaluating Technological Efficiency of Acidizing

The developed regression equations and certain optimal technological parameters of acid stimulation enable a comprehensive evaluation of prospects of such operations, which was carried out using the example of a production well with the following characteristics: the effective oil-saturated thickness was 6.1 m, permeability of the remote (borehole) zone was 20 (39)·10^{-3} μm^2, the water cut was 2.6 %, the current well production rate for oil was 5.0 t/day, the reservoir (borehole) pressure was 9.6 (8.6) MPa.

According to the results of the laboratory experiments, the treatment efficiency increases when the amount of the injected solution increases, therefore, the design of operations and the calculation of their success is carried out for various specific volumes of the agent: 4 (minimum, recommended); 6; 8 and 10 m^3/m. When re-perforating, it is recommended to use an additional injection of the acid in a volume of 0.5 m^3/m for an additional cleaning of perforations.

After determining the absolute increase in production oil, using the multivariate regression models, the potential incremental oil production (IOP) and the duration of the effect were evaluated based on the dependencies built on the basis of the acid treatments performed earlier (Fig. 10).

Table. 2 presents the design of various options for carrying out operations and their expected effectiveness.

By analyzing the data in Table. 2, we can conclude that in the well under consideration, the reservoir re-perforation with a subsequent chemical treatment is characterized by a greater technological efficiency than the basic acid treatment. The choice of a specific volume of the acid composition is recommended to be made depending on the current economic conditions in the region of oil production.

Table 2

Optimal design and predicted efficiency of various options of BHT

Technological parameter/effect	Value of indicator			
	Basic acidic treatment			
Specific volume of acid composition, m^3/m	4.0	6.0	8.0	10.0
The volume of acid composition, m^3	24.4	36.6	48.8	61.0
Exposure time, h	Without exposure			
Injection rate, m^3/h	9.9			
Expected injection pressure, MPa	0.3			
Specific increase in oil production rate, t/(day·m)	0.52	0.64	0.76	0.88
Absolute increase in oil production, t/day	3.2	3.9	4.6	5.4
Incremental oil production, t	425	586	766	964
Duration of effect, day	194	250	308	368
	Re-perforation with acidizing			
Specific volume of acid composition, m^3/m	4.5	6.5	8.5	10.5
The volume of acid composition, m^3	27.5	39.7	51.9	64.1
Exposure time, h	Without exposure			
Injection rate, m^3/h	9.9			
Expected injection pressure, MPa	0.3			
Specific increase in oil production rate, t/(day·m)	0.47	0.69	0.92	1.14
Absolute increase in oil production, t/day	2.8	4.2	5.6	7.0
Incremental oil production, t	584	1229	2092	3165
Duration of effect, day	349	674	1077	1552

Conclusions

1. A method for predicting the effectiveness of acid treatments based on mathematical and physical modeling was developed, justified and tested using the example of a carbonate production facility in Perm Kray. This approach can be used to rank candidate wells, form and adjust targeted programs for geological and technical operations for a short and long term, select the method of stimulation, allowing a more targeted use of acid treatments during the development of hydrocarbon deposits.

2. By using actual geological field materials, we developed the multidimensional regression equations to predict effectiveness of acid treatments in order to accurately estimate the result of treating borehole zones of wells with chemical agents.

3. During the laboratory studies of the core samples, we determined the optimal technological parameters of the treatment, the prospects of the bulk acid treatments without the acid exposure stage in the reservoir per reaction to predict clogging of the reservoir void space.

4. The integration of the results of the multivariate regression analysis and laboratory experiments made it possible to determine the technological efficiency of geological and technical operations (in the considered example, the estimated additional oil production was 0.4-3.2 thousand tons, depending on the volume of the injected acid and the method of affecting the borehole zone). The choice of a specific volume of the acid composition is recommended depending on the current economic conditions in the region of oil production.

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