ISSN 2712-8008
Volume / Том 21 №4 2021
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622.245
Article / Статья

Self-Diverting Acids as a Method for Intensification of Oil Production in Carbonate Reservoirs

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Самоотклоняющиеся кислотные составы как метод интенсификации добычи нефти в карбонатных коллекторах

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Received / Получена: 09.04.2021. Accepted / Принята: 30.07.2021. Published / Опубликована: 01.10.2021

Keywords:
self-diverting acids, filtration tests, technology efficiency, permeable intervals of a productive formation, acid treatment, core model, permeability build-up, treatment of the bottom-hole formation zone, inflow profile redistribution, blocking of washed out intervals, acid redistribution, water cut, residual oil reserves, laboratory investigations, viscosity, composition depletion by reaction with carbonate rock.

Currently, most residual recoverable oil reserves of the fields are located in complex layered heterogeneous carbonate reservoirs. Improving the efficiency of field development in conditions of uneven development of reserves along the section is complicated by an increase in water cut that occurs as reserves are recovered. In this regard, the process of searching for candidate wells for acidising becomes more complicated, and there is a need to use new technologies for stimulating the formation. In particular, the use of diverting agents in hydrochloric acid treatment often becomes a prerequisite for a successful treatment of the bottom-hole zone. The results of laboratory studies and work performed in wells are generalised and analysed, as well as the correctness of methodological approaches in studies of self-deviating acids is confirmed, taking into account the actual results obtained on wells.
The results of laboratory investigations of self-deviating acids in the "free volume" and on core material are described, the testing of acid compositions in four wells, including the results of flow measurements before and after treatment, is analysed.
The analysis of works showed that according to the results of flow measurements carried out in the wells, the inflow profile redistribution was recorded, which was also noted at the stage of filtration studies on two-layer multi-permeable models. The promising areas for applying self-diverting acid are wells with intervals not connected to development in the presence of permeability contrast, including after standard acid treatments. It is necessary to test the technology at objects with a small formation thickness to ensure a higher specific reagent consumption, taking into account the high cost of self-diverting acids.

Ключевые слова:
самоотклоняющиеся кислотные составы, фильтрационные испытания, эффективность технологии, проницаемые интервалы продуктивного пласта, кислотная обработка, керновая модель, восстановление проницаемости, обработка призабойной зоны пласта, перераспределение профиля притока, блокирование промытых интервалов, перераспределение кислоты, обводненность продукции, остаточные запасы нефти, лабораторные исследования, вязкость, истощение состава при реакции с карбонатной породой.

В настоящее время большая часть остаточных извлекаемых запасов нефти месторождений находится в сложнопостроенных слоисто-неоднородных карбонатных коллекторах. Повышение эффективности разработки месторождений в условиях неравномерной выработки запасов по разрезу осложняется ростом обводненности, происходящей по мере выработки запасов. В связи с этим усложняется процесс поиска скважин-кандидатов для проведения кислотных обработок, появляется необходимость использования новых технологий воздействия на пласт. В частности, использование отклоняющих агентов при солянокислотной обработке нередко становится необходимым условием для успешного проведения обработки призабойной зоны. Обобщены и проанализированы результаты лабораторных исследований и выполненных работ на скважинах, в том числе подтверждена корректность методических подходов при проведении исследований самоотклоняющихся кислотных систем с учетом фактически полученных результатов на скважинах.
Описаны результаты лабораторных исследований самоотклоняющихся кислотных составов в «свободном объеме» и на керновом материале, проанализировано испытание кислотных составов на четырех скважинах, в том числе результаты потокометрических исследований до и после обработки.
Анализ работ показал, что по результатам потокометрических исследований, проведенных в скважинах, зафиксировано перераспределение профиля притока, что также отмечалось на этапе фильтрационных исследований на двухслойных разнопроницаемых моделях. Перспективной областью применения самотклоняющихся кислотных составов являются скважины с не подключенными в разработку интервалами при наличии контраста проницаемости, в том числе после осуществления стандартных кислотных обработок. Необходимо испытание технологии на объектах с небольшой мощностью пласта с целью обеспечения большего удельного расхода реагентов с учетом высокой стоимости самотклоняющихся кислотных составов.

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Please cite this article in English as:
YakimovaT.S. Self-diverting acids as a method for intensification of oil production in carbonate reservoirs. *Perm Journal of Petroleum and Mining Engineering*, 2021, vol.21, no.4, pp.171-175. DOI: 10.15593/2712-8008/2021.4.4

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Якимова Т.С. Самоотклоняющиеся кислотные составы как метод интенсификации добычи нефти в карбонатных коллекторах // Недропользование. – 2021. – Т.21, №4. – С.171–175. DOI: 10.15593/2712-8008/2021.4.4

Introduction

Yearly deterioration of the reserves' structure, growing watercut of the recovered product requires the improvement of the oil mining intensification technologies. One of such technologies is the self-diverting acid compositions (SDAC) for the carbonate-type rocks. The technology principle is based on the compositions' ability to produce gel that diverts the following composition portions into less permeable areas as they react with the reservoir rock. This is how sap-rot channel network is created for better volume treatment. At the same time, the composition viscosity reduces to the initial value and below as the acid gets fully neutralized [1, 2].

Laboratory Test Results

In order to confirm the stated properties of the reagent [3], laboratory tests were carried out. There are various approaches to modelling self-diverting systems in the laboratory medium [4]; this study presents a standard set of test in "free volume", filtration tests made on single core samples, as well as filtration tests on two-layer multi-permeable models. Geological and physical properties of the test subject:

– oil viscosity in the formations – 20 mPa·s;

– formation temperature – 27 °C;

– gas permeability range:

– group 1 (low-permeability sublayer) – 0.01–0.035 μm^2;

– group 2 (high-permeability sublayer) – 0.035–0.069 μm^2.

To confirm the stated properties, viscosity changes were measured progressively as the self-diverting composition was depleting (Fig. 1).

The laboratory test results confirmed the self-diverting composition's viscosity-gaining capacity in the reaction with a carbonate rock; after the acid consumption, the composition viscosity reduced by four times compared with the initial value. This acid system behavior yields a conclusion on the possibility of the composition's temporary colmation of the most permeable interval for the re-distribution of the next portion of the acid composition into the low-permeability part of the reservoir without leaving any remnant colmation of the formation.

Generally, the "free volume" tests of the acid and self-diverting compositions allowed the following conclusions:

– both reagents are compatible with the formation water and oil of the test subject;

– the use of acid composition slows down the reaction with the carbonate rock compared with the hydrochloric acid of the same concentration; the slow down degree for various core materials varies from 0.5 to 0.66 units;

– when neutralized with the core material, the self-diverting composition satisfies the claimed properties: its viscosity gradually increases to the exhaustion degree 60–70 %, then the system viscosity rapidly falls and at the 100 % exhaustion gets below 10 mPa·sec, which is less than the initial SDAC viscosity by approximately four times.

The filtration test for the determination of the permeability value and modelling of the SDAC effect and the acid composition impact was carried out on the PIK-OFP unit. A core sample was settled in the core holder with a lateral hydroclamp to prevent filtration along the lateral surface of the sample.

At the first stage of the filtration stage, the effect made by SDAC and the acid composition on the reservoir rock matrix was studied (100 % water saturated core samples).

Filtration test procedure:

– determination of permeability before the acid composition injection;

– modelling the acid composition injection process;

– acid composition filtration through the core sample in the "well – reservoir" direction at the injection rate of 1 cm^3/min before the "breakthrough", i.e. the moment of formation of a high-permeability canal with simultaneous rapid injection pressure

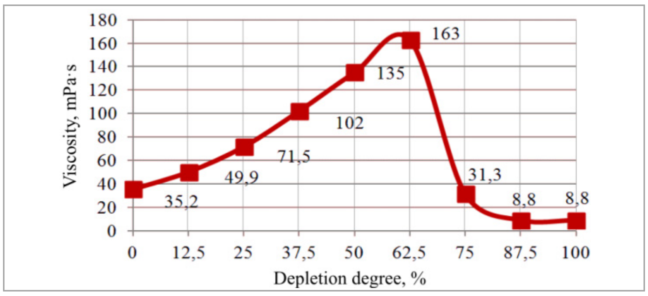

Fig. 1. SDAC viscosity dynamics at the reaction with the core material under the given formation temperature

drop. Recording the amount of the acid composition injected before the breakthrough;

– the acid composition maturing in the pore space is not foreseen (according to the technology authors);

– determination of permeability after the acid composition injection: filtration of the reservoir fluid through the core sample in the "reservoir – well" direction until the normalization of the system pressure (at not less than 3 V_{pore}) followed by permeability measurement;

$$K_{rest} = K_{perm2} / K_{perm1}, \qquad (1)$$

where K_{rest} is the permeability restitution factor, units; K_{perm1} is the permeability factor before acid injection, μm^2; K_{perm2} is the permeability factor after acid injection, μm^2.

The filtration tests brought the following results:

1. For the group of gas permeability from 0.01 to 0.035 μm^2, the water permeability restitution factor constituted:

– for SADC: 118.42 – 180 units;

– for acid composition: 60.53-135.42 units.

2. For the group of gas permeability from 0.035 to 0.07 μm^2, the water permeability restitution factor constituted:

– for SADC: 33.72–69,60 units;

– for acid composition: 26.58–28.08 units.

In the acid composition filtration process, we see a continuous growth of the injection pressure to the moment of "breakthrough" (abrupt pressure drop) followed by the formation of a high-permeability canal.

At the second stage of the filtration test, the SADC and acid composition effect on the oil permeability of the core samples (oil saturated core samples with residual water saturation) was studied. The test procedure is the same as at the previous stage.

The filtration tests brought the following results:

1. For the group of gas permeability from 0.01 to 0.035 μm^2, the oil permeability restoration factor constituted:

– for SADC: 171,07–173,13 units;

– for acid composition: 136.29–170.73 units.

2. For the group of gas permeability from 0.035 to 0.07 μm^2, the water permeability restitution factor constituted:

– for SADC: 46.34–47.01 units;

– for acid composition: 37.68–40.00 units.

Same as at the first stage, in the acid composition filtration process, we see a continuous growth of the injection pressure to the moment of "breakthrough" followed by the formation of a high-permeability canal. Based on the results analysis, it can be stated that the "breakthrough" of the oil saturated core samples requires approximately 30 % less SADC pore volume injection than acid composition.

At the third stage of the filtration test, the efficiency of the acid treatment technology was assessed in an uneven reservoir based on two-layered core models of different permeability, consisting of core samples with a preserved diameter. The uneven reservoir model consists of two parallel core models with one input for fluids and reagents to model the low-permeablity and high-permeability sublayers.

Filtration test procedure:

A. Oil permeability determination before reagent injection: filtration of the reservoir oil model through the oil-saturated uneven core model with residual water saturation in the "reservoir – well" direction to the stabilization of the system pressure (in the volume not less than 3 V_{pore}) with further oil permeability determination in the following order:

1) on a core model to simulate a low-permeability sublayer;
2) on a core model to simulate a high-permeability sublayer;
3) for an uneven model in general.

Permeability determination for an uneven reservoir model requires a selection of an injection rate that provides the fluid filtration through the high-permeability model of 10 cm^3/min.

B. Reagent injection modelling.

The reagents are injected into an uneven core model in the "well – reservoir" direction stage by stage:

1) SADC injection at the rate selected at the permeability determination stage at the amount of 0.3 V_{pore} of a high-permeability model or 0.1 V_{pore} of a low-permeability model (whichever is earlier);
3) acid composition injection at the rate selected at the permeability determination stage before the "breakthrough", moment of formation of a high-permeability canal and an abrupt fall of the injection pressure;
3) acid composition and SADC maturing in the pore space is not foreseen (according to the technology authors).

C. Oil permeability determination after reagent injection: filtration of the reservoir oil model through an uneven core model in the "reservoir – well" direction to the stabilization of the system pressure (in the volume not less than 3 V_{pore}) with further oil permeability determination in the following order:

1) on a core model to simulate a low-permeability sublayer;
2) on a core model to simulate a high-permeability sublayer;
3) for an uneven model in general.

D. Photograph of the core end surfaces after reagent injection.

E. Determination of the permeability restitution factor for the reservoir oil model, for the low-, high-permeability and uneven core models separately.

The test results are presented in Table 1.

Industrial Test Results

There is an extensive experience of acid treatment with SADC [1, 5–45]. This paper analyzes the experience of works in the Timano-Pechorskaya oil and gas province fields. The technology has been tested on four wells; the bottomhole technological process foresaw the following stages:

1) injection of an acid composition at the volume of the pumping and compression pipes with an uninstalled packer;
2) packer installation;
3) SADC injection;
4) injection of the remaining acid composition volume;
5) pressing the acid composition with technical water at the pumping and compression pipes' volume + 1.5 m^3.

The main technological parameters of the bottomhole zone (BHZ) treatment are presented in Table 2.

The injection schedule of well 1 has been analyzed: the injection pressure rose only at the pressing stage, approximately 100 minutes after the SADC input into the reservoir. This pressure drop type may be related to the low speed of the SADC and rock reaction, as a result of which the SADC viscosity rate was gained slower. Moreover, the mineral compositions of the rocks were analyzed; the core samples from the site were taken from one well only. According to the core samples' mineral composition studies, the permeable intervals of the productive reservoir are almost completely made up of dolomite (Fig. 2), which explains the low speed of the SADC reaction with the rock, and, therefore, low viscosity rate growth.

The inflow profile studies before and after the bottomhole treatment were only carried out in wells No. 2 and 4 (Fig. 3). According to the completed studies, before the bottomhole treatment, in well No. 2 the main fluid inflow (87 %) was coming from the lower part of the perforation interval below 1346.7 m. After the bottomhole operation, 100 % of the inflow falls on that interval alone. However, the involvement of the interval of

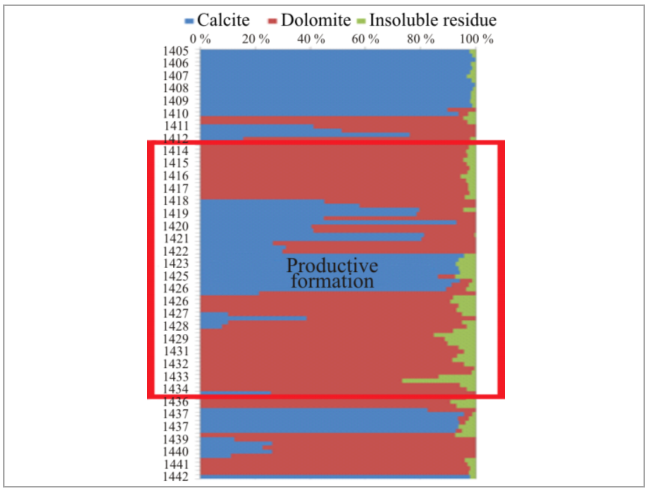

Fig. 2. Mineral rock composition according to the core analysis

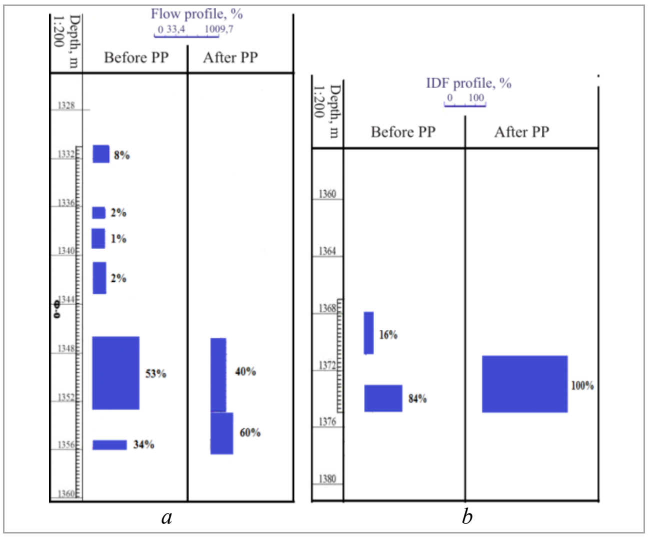

Fig. 3. Inflow profiles before and after bottomhole operations in well 2 (*a*) and 4 (*b*)

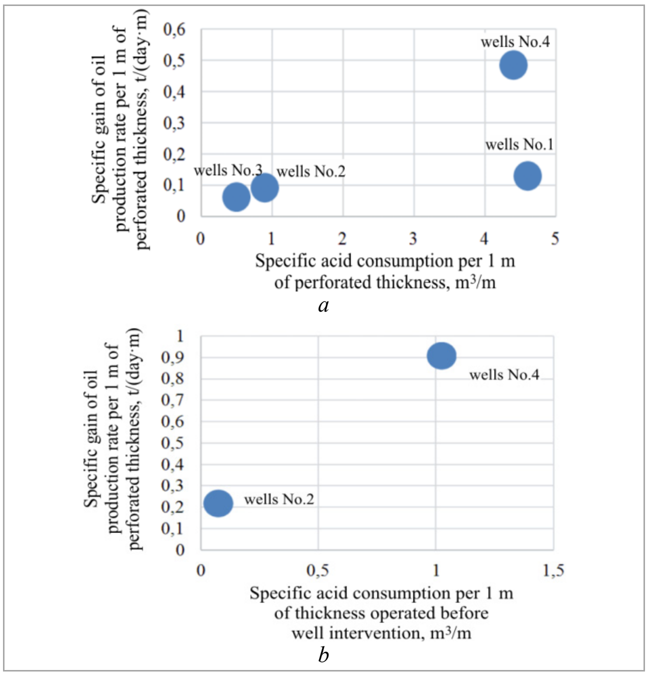

Fig. 4. Distribution of the specific oil production increment depending on the specific acid consumption: *a* – per one meter of the perforated reservoir thickness; *b* – per one meter of the reservoir oil pay before well intervention

Table 1

Results of the technology tests on two-layered uneven models

Core sample	Oil permeability before reagent injection, K_{perm1}, μm²	Reagent injection rate, cm³/min	SADC injection volume, cm³(V_{pore})	P_{max} at SADC, MPa	Acid composition injection volume, cm³ (V_{pore})	P_{max} at acid composition injection, MPa	Oil permeability after reagent injection K_{perm2}, μm²	K_{rest}, units
Uneven model 1								
1	0.0024	12.0	3.1 (0.074)	0.52	96 (2.30)	1.42	0.8557	361.25
2	0.0121		15.5 (0.300)		94 (1.82)		0.5704	46.99
Model No. 1	0.0073		–		–		0.7131	98.30
Uneven model No. 2								
3	0.0050	15.4	4.8 (0.102)	0.74	67 (1.42)	1.26	0.6484	129.84
4	0.0094		10.2 (0.178)		113 (1.97)		0.8645	92.21
Model No. 2	0.0072		–		–		0.7565	105.29

Table 2

Main technological parameters of the bottomhole zone treatment

Well No.	Volume of acid composition, m³	Volume of SADC, m³	Specific acid consumption per one meter of perforated thickness³/m	SADC to acid volume ratio, unit fractions	Maximum injection pressure, MPa
1	25	10	4.6	0.40	1.8
2	17	8	0.9	0.47	5.0
3	12	5.5	0.5	0.46	0.0
4	22.5	9.5	4.4	0.37	3.0

Table 3

Technological efficiency of the bottomhole treatment

Well No.	Well operation mode						Oil production increment, tonnes/day
	before well intervention			after well intervention			
	Q_{oil}, tonnes/day	Q_{fluid}, m³/day	water %	Q_{oil}, tonnes/day	Q_{fluid}, m³/day	water %	
1	2.6	4.9	40	3.6	9.0	25	1.0
2	1.1	2.0	38	3.8	24.4	80	2.7
3	1.5	2.0	16	3.9	7.6	28	2.4
4	1.5	3.0	43	5.4	9.3	31	3.9

Note: well intervention – hydrotechnical operations.

1352.9–1355.4 m is also noted, together with the decreasing inflow share of the interval 1346.7–1352.7 m from 53 to 40 %. The absence of inflow from the upper part of the reservoir after the bottomhole treatment may be related to the lower depression of the reservoir during the research (after swabbing – 250 m, during the research, before bottomhole treatment – 969 m). Besides, the upper part of the reservoir could not be exposed to the acid effect during the bottomhole treatment due to the low specific SADC consumption and the low-acid content per one meter of perforated reservoir thickness, or due to the high contrast of permeability and pore pressure compared to the bottom part of the reservoir.

According to the completed studies, before the bottomhole treatment, in well No. 4 the main fluid inflow (84 %) was coming from the lower part of the perforation interval below 1373.3 m. After the bottomhole treatment, the involvement of the interval 1371–1373.3 m was noted. The work of the interval 1368–1370.8 m which used to produce 16 % of the inflow is not seen, which may be explained by the lower depression of the reservoir during the research (after swabbing – 608 m, during the research, before bottomhole treatment – 956 m). This way, in this well, just like in well No. 2, in a lower depression of the reservoir, a new interval got involved in the work, but the most productive interval inflow share did not decrease.

Thus, the flow measurement before/after the bottomhole treatment, the SADC diverting effect discovered at the filtration test stage on the uneven two-layer reservoir models, has proven itself in the well conditions.

Table 3 presents the technological efficiency of the bottomhole treatment operations.

The average oil net pay increment constituted 2.5 tonnes/day; the greatest oil net pay increment (3.9 tonnes/day) was achieved in well No.4; it also showed the highest specific increment per one meter of the perforated reservoir thickness (0.49 tonnes/(day·m)). At that, exclusive of well No.1, there is a tendency of the specific oil pay increment growth caused by the specific acid consumption: in wells No. 2 and 3, the specific acid consumption was 6.3 times less than in well No. 4, and the specific oil pay increment was 6.1 times less (Fig. 4, *a*).

At the same time, in the wells with the flow measurement completed before well intervention, a direct dependence of their efficiency on the specific acid consumption was noticed (Fig. 4, *b*).

Conclusion

1. During the works carried out on all wells except for well No. 3, the injection process was accompanied by the well head pressure growth, which may indirectly indicate the SADC diverting effect.

2. The mineral composition studies prove the high dolomite content in the productive reservoir section; therefore, due to the low SADC and rock reaction rate, the diverting effect may manifest with a delay. Technology trial on a site with lower dolomite content in the wells is recommended.

3. The flow measurement carried out in the wells No. 2 and 4 showed the inflow profile redistribution, which was also found at the stage of filtration studies on two-layer multi-permeable models.

4. The promising areas for applying self-diverting acid are wells with intervals not connected to development in the presence of permeability contrast, including after standard acid treatments.

5. It is necessary to test the technology on objects with a small formation thickness to ensure a higher specific reagent consumption, taking into account the high cost of self-diverting acids.

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