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THE INFLUENCE OF ACID CONCENTRATION AND INJECTION RATE ON THE WORMHOLE DEVELOPMENT IN FORMATION CONDITIONS. A LABORATORY STUDY

R.A. Khuzin, G.P. Khizhniak[1]

Gazpromneft Badra B.V. (335 Royal Tulip Al-Rashid Hotel, Baghdad, 8070, Republic of Iraq)
[1]Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)

ЛАБОРАТОРНЫЕ ИССЛЕДОВАНИЯ ВЛИЯНИЯ КОНЦЕНТРАЦИИ И СКОРОСТИ ЗАКАЧКИ КИСЛОТЫ НА РАЗВИТИЕ ЧЕРВОТОЧИН ПРИ ПЛАСТОВЫХ УСЛОВИЯХ

Р.А. Хузин, Г.П. Хижняк[1]

Газпромнефть Бадра Б.В. (8070, Ирак, г. Багдад, Ройял Тьюлип Аль-Рашид Хоутел, офис 335)
[1]Пермский национальный исследовательский политехнический университет (614990, Россия, г. Пермь, Комсомольский проспект, 29)

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Carbonate rocks contain about 60 % of global oil and gas reserves. Stimulation of wells tapping into carbonate reservoirs is often performed using hydrochloric acid treatments based on the chemical reaction of hydrochloric acid with carbonate minerals.

Carbonate reservoirs generally exhibit significant inhomogeneity, therefore the acid being injected into the formation causes uneven rock dissolution in the near-wellbore region, resulting in the emergence of highly conductive flow channels (wormholes) with complex geometry. They ensure a good hydrodynamic connection between the well and the formation. Each specific rock-acid compound system has an optimum injection rate which can help form long weakly ramified wormholes at minimum acid injection volume. The optimum injection rate value is influenced by many factors, such as pressure, temperature, acid concentration, solution composition, mineral composition of rock etc. As of today, laboratory research is the main method to determine the optimum parameters for treating the near-wellbore formation region with acid. The paper summarises the results of the analysis examining the influence of various factors on the optimum injection rate and the amount of injected pore volumes of an acid compound until a wormhole breakthrough. It is shown that the factors have a cumulative effect on the effectiveness of the acid treatment and have to be considered simultaneously in laboratory tests. The results of the performed analysis have been taken into account when planning further laboratory research.

Within the design scope of hydrochloric acid treatments in wells of one of Iraq's carbonate fields, laboratory tests have been conducted to assess the impact of acid concentration and injection rate on the effectiveness of acid stimulation in the conditions that were expected in case of the hydrochloric acid treatment. The determined injection parameters help obtain an optimum structure of wormholes at a minimum acid injection volume.

The results of the performed research have been successfully used to design hydrochloric acid treatments in wells of the field under study.

Ключевые слова:
карбонаты, известняк, доломит, солянокислотная обработка, червоточины, околоскважинная зона пласта, скорость закачки, температура, давление, концентрация кислоты, насыщение, композиционный состав, фильтрационные свойства, минеральный состав, структура порового пространства, кавернозность, перфорация, размер образцов, геометрия потока, Бадра, Ирак, керн, дифракционный анализ, компьютерная томография.

Карбонатные породы содержат около 60 % мировых запасов нефти и газа. Для стимуляции скважин, вскрывающих карбонатные коллекторы, широко используются солянокислотные обработки, в основе которых лежит химическая реакция соляной кислоты с карбонатными минералами.

Карбонатные коллекторы, как правило, обладают значительной неоднородностью, поэтому при закачке кислоты в пласт в призабойной зоне скважины происходит неравномерное растворение породы кислотой, в результате чего образуются высокопроводящие каналы фильтрации (червоточины) сложной геометрии, обеспечивающие хорошую гидродинамическую связь скважины с пластом. Для определенной системы «порода – кислотный состав» существует оптимальная скорость закачки, которая позволяет получать длинные малоразветвленные червоточины при минимальном объеме закачки кислоты. На величину оптимальной скорости закачки оказывает влияние множество факторов, таких как давление, температура, концентрация кислоты, композиционный состав раствора, минеральный состав породы и т.д. Основным методом определения оптимальных параметров кислотного воздействия на околоскважинную зону пласта на сегодняшний день являются лабораторные эксперименты.

В работе приведены сводные результаты анализа влияния различных факторов на оптимальную скорость закачки и величину прокачанных поровых объемов кислотного состава до момента выхода червоточины из образца. Показано, что факторы комплексно влияют на эффективность кислотного воздействия и требуется их одновременный учет при проведении лабораторных экспериментов. Результаты выполненного анализа были учтены при планировании дальнейших лабораторных исследований.

В рамках проектирования солянокислотных обработок на скважинах одного из карбонатных месторождений Ирака проведены лабораторные опыты по оценке влияния концентрации кислоты и скорости закачки на эффективность кислотного воздействия при условиях, ожидаемых в случае применения солянокислотной обработки. Определены параметры закачки, позволяющие получать оптимальную структуру червоточин при минимальном объеме закачки кислоты.

Результаты выполненных исследований успешно использовались при проектировании солянокислотных обработок на скважинах рассмотренного месторождения.

Rinat A. Khuzin (Author ID in Scopus: 57205219438) – Head of Development Department (tel.: +007 968 662 14 56, e-mail: Khuzin.ra@gazpromneft-badra.com). The contact person for correspondence.
Grigoriy P. Khizhnyak (Author ID in Scopus: 36711848000) – Doctor of Engineering, Associate Professor at the Department of Oil and Gas Technologies (tel.: +007 342 219 82 92, e-mail: xgp@mail.ru).

Хузин Ринат Альвертович – начальник управления разработки (тел.: +007 968 662 14 56, e-mail: Khuzin.ra@gazpromneft-badra.com). Контактное лицо для переписки.
Хижняк Григорий Петрович – доктор технических наук, доцент, заведующий кафедрой нефтегазовых технологий (тел.: +007 342 219 82 92, e-mail: xgp@pstu.ru).

Introduction

Carbonate rocks contain about 60 % of global oil and gas reserves [1–4]. These rocks mostly include sedimentary formations consisting of 50 % and more carbonate minerals [5], the major part of which are calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). To intensify a fluid influx to a well tapping into the carbonate reservoir, hydrochloric acid treatments (HATs) of the near-wellbore formation region (NWFR) are widely used. This stimulation type is based on the interaction of acid solutions, mostly derived from hydrochloric acid (HCl), with carbonate minerals. As multiple laboratory tests have shown, the injection of acid into the carbonate reservoir results in the formation of the so-called wormholes, or highly permeable channels with complex geometry that penetrate the formation to the depth of several meters and thus ensure a good hydrodynamic connection between the formation and the wellbore (Fig. 1).

The shape and penetration depth of wormholes depends on many factors, such as acid solution composition, mineral composition of the rock, formation saturation, rock inhomogeneity, injection rate, well completion type etc.

In HAT design, one of the main goals is to select optimum acid compounds and injection parameters for the conditions of a specific deposit, to obtain long weakly ramified wormholes at a minimum acid injection volume.

As of today, the main method for studying the processes occurring during a HAT is laboratory tests. As a rule, it is difficult to design the tests so as to consider all possible factors influencing the acid treatment effectiveness. The analysis has shown that the purpose of the majority of the published works was to study the influence of individual factors on the acid stimulation effectiveness. However, a possible simultaneous influence of several factors was not considered. Besides, in most works, the tests were performed in conditions that vastly varied from the real HAT conditions. Practical use of such results can lead to a significant error in the obtained estimates.

The current task is to determine the factors that have to be considered simultaneously in laboratory studies and to obtain correlation dependencies that enable practical forecasting of the wormhole development processes in the near-wellbore formation region.

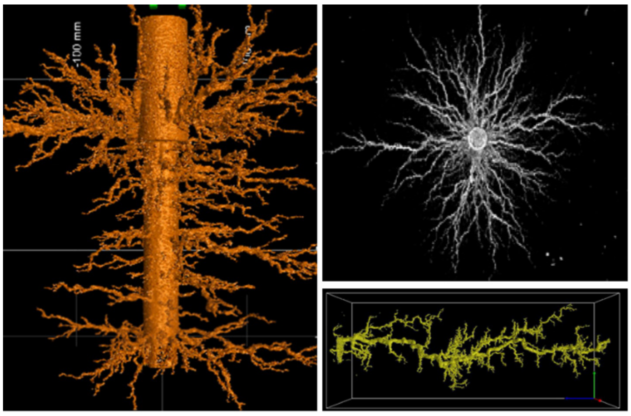


Fig. 1. 3D-visualization of wormholes based on computed tomography [6–8]

A concise analysis of factors influencing the acid stimulation effectiveness

Acid stimulation effects on carbonate formations have been extensively studied in the literature. As a rule, the authors use laboratory tests to research the influence of one or several factors on the acid treatment effectiveness. Such factors include:

- acid injection rate and volume [9–16];
- stimulation temperature [9, 10, 17, 18];
- hydrochloric acid concentration [9, 10, 14, 17–19];
- stimulation pressure [20];
- fluid saturation of samples [21–24];
- composition of injected solutions [9, 14, 15, 17, 18, 23, 25–49];
- size of samples [17, 19, 45];
- flow geometry (radial, linear) [6, 10, 11, 50–53];
- mineral composition (calcite, dolomite) [9, 54];
- flow properties and pore structure [10, 14, 17, 28, 40, 52, 54–60];
- influence of well completion technology and stimulation features [61–63].

It does not seem possible to review the entire scope of the performed studies, due to a large variety of acid compounds used, conditions emerging during the injection, composition of NWFR saturating fluids, pore structure, rock mineral composition etc.

As multiple experiments have shown, any given rock-acid compound system can produce various rock dissolution structures depending on the injection rate (Fig. 2):

- face dissolution;
- formation of conic wormholes;

- formation of dominant wormholes (long, narrow, weakly ramified wormholes – optimum result);
- strongly ramified wormhole structure;
- uniform dissolution.

At the minimum injection rates, the entire solution reacts upon entry into the sample and dissolves it completely. In this case, to achieve a certain penetration depth, a significant volume of acid compound (AC) is required. At a higher injection rate, the acid penetrates the rock and forms a dissolution channel – a wormhole; however, a significant portion of the solution reacts with the wormhole walls, thereby creating its conic structure. The AC volume to achieve a certain depth of wormhole penetration is significantly lower compared to the face dissolution. If the injection rate is sufficient to deliver the AC to the wormhole tip, then the reacting results in its further lengthening and formation of the so-called dominant wormhole which develops through dissolution of pores with a maximum diameter. This structure is the most optimum one since it helps reach the required penetration depth at the minimum injection volume. Higher injection rates lead to the formation of ramifications from the dominant wormhole since the solution becomes pressured into the minor pores and the length-wise growth of the wormhole slows down, hence increasing the overall AC volume required to achieve the necessary penetration depth. At extremely high injection rates, the acid penetrates even smaller pores resulting in their uniform dissolution and an increase of the required AC volume to achieve the required penetration depth.

The results of laboratory tests in their most simple interpretation can be presented as a dependence of the number of injected pore volumes of the solution until a wormhole breakthrough (*PVBT*) on the injection rate (*Vi*) (Fig. 3). The figure shows the results of several tests performed in various conditions. The minimum point on each curve determines the optimum injection rate.

In order to determine the factors that have to be considered in the laboratory tests for studying the acid stimulation effectiveness, an analytical review of the published research has been performed.

Table 1 summarises the results of the analysis examining how different factors impact on the optimum injection rate and *PVBT* value, along with the justification of their importance and the possibility to take them into account in the laboratory conditions for commercial-scope tests.

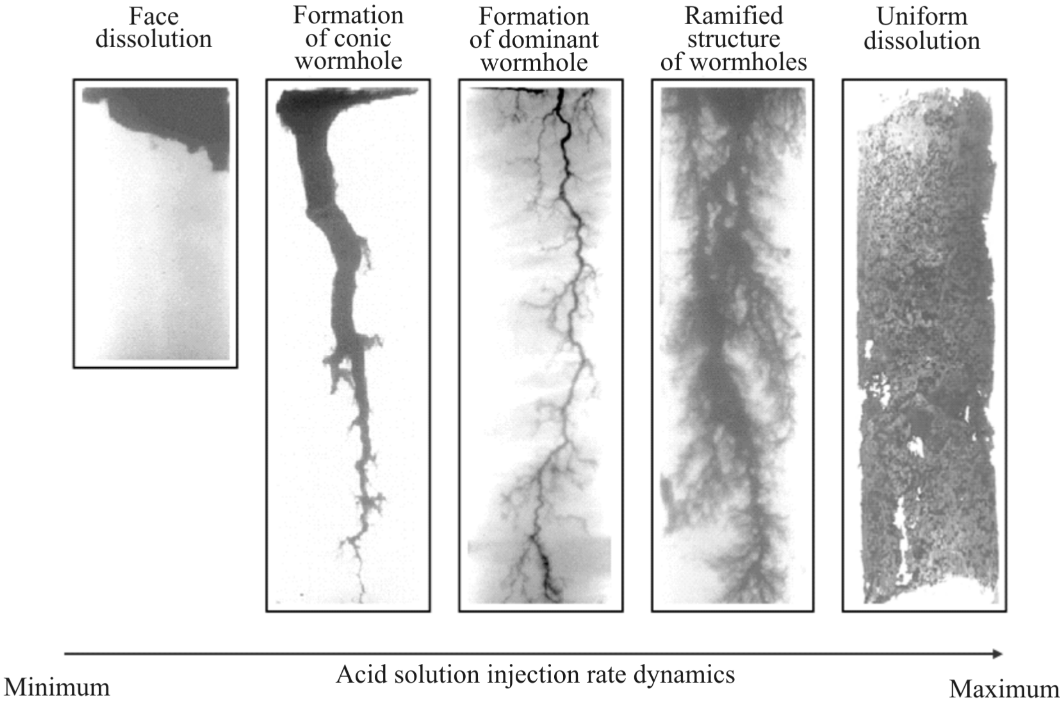


Fig. 2. The appearance of dissolved pore space obtained by injection of hydrochloric acid into the linear core sample at various injection rates [12]

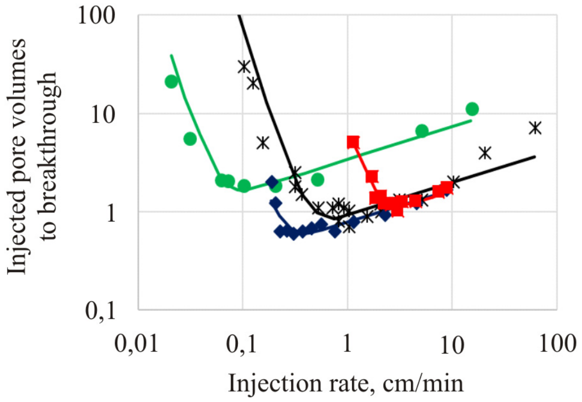


Fig. 3. The results of the laboratory tests to assess the wormhole development effectiveness [64]

As evident from Table 1, all considered factors, except pressure (in case it exceeds the pressure of the generated CO_2 gas transition to the liquid condition or the supercritical fluid condition), have a high impact on the results obtained in the course of the laboratory studies. It suggests that they have to be taken into account during test design. The dynamics of some of the factors can have a divergent impact on the optimum injection rate and *PVBT* value. Besides, a simultaneous manifestation of different factors, which is normally observed in practice, can also result in divergent dynamics of the optimum injection parameters. It is difficult to take into account some of these factors in mass laboratory tests due to the limitation of sample size and used equipment. To take these factors into account, it is necessary to use the correlations that are discussed in the research literature.

The analysis has shown that to obtain the correlation dependencies that enable practical forecasting of the wormhole development in NWFR, a laboratory test have to be conducted in the conditions that approximate to those expected during the HAT, and on representative core samples from the specific field.

Table 1

The summary results of the analysis of various factors impact on the optimum injection rate and *PVBT* value

Factor		Importance of consideration in laboratory tests	Optimum injection rate dynamics vs. parameter growth	*PVBT* dynamics vs. parameter growth	Possibility to consider HAT expected data in laboratory tests
Temperature		High	Increase	Divergent	Possible
HCl concentration		High	Increase	Decrease	Possible
Pressure	below 69 atm (1000 psi)	High	Decrease	Increase	Possible
	above 69 atm (1000 psi)	Low	Low impact	Low impact	–
Hydrocarbon saturation		High	Decrease	Decrease	Possible
Injected fluid composition		High	Divergent	Divergent	Possible
Impact of flow properties, pore structure and mineral composition		High	Divergent	Divergent	Possible
Impact of sample size		High	Increase	Increase	Use of samples commensurate with NWFR is problematic
Impact of perforation channels purity		High	Decrease	Decrease	Use of samples commensurate with influence of perforation channels in NWFR is problematic
Impact of jet effect due to the well stimulation features		High	Decrease	Decrease	Use of samples commensurate with NWFR is problematic
Transfer from linear to radial samples		High	Increase	Increase	Use of samples commensurate with NWFR is problematic

Laboratory study of the concentration and injection rate influence on hydrochloric acid solutions in formation conditions of one of the Iraqi fields

Object of the study

The object of the study is a field located in Zagros oil province, Iraq. The main production object is the Mauddud Upper Cretaceous formation having eight determined strata (A, B, C, D, E, F, G, H). The main volume of the reserves (about 80 %) is concentrated in B and D strata that produce up to 94 % of the field oil. Due to these reasons, the research was focused on these strata. The productive strata are represented by carbonate porous type reservoirs containing light crude oil. Due to the geological peculiarities, the productive strata penetration occurs at significant overbalance pressure, resulting in NWFR clogging. As the experience of testing in the first development wells has shown, to obtain a commercial oil influx, it is necessary to stimulate the wells with acid compounds. The laboratory tests using core samples selected from the development wells have been conducted in order to study the strata properties and optimize stimulation of the producing wells.

Determining the test conditions

When determining the conditions for the laboratory tests that suggested an injection of acid compounds into core samples, the aforementioned analysis of factors influencing the test results have been taken into account. Therefore, it was decided to conduct the experiments in the conditions reproducing those expected in the well stimulation (temperature, pressure, saturation, reservoir fluids viscosity, acid composition and concentration). The experiments were aimed at assessing the influence of the acid solution injection rate and concentration.

Samples conditioning

Prior to checking if the samples are representative, a CT scanning was performed, the samples were cleaned and conditioned for the research.

In order to determine the quantitative composition of minerals contained in the samples, X-ray diffraction analysis (XRD) was performed. The analysis results for 18 samples (Table 2) have shown that the rock consists of micritic limestone with prevailing calcite (more than 95 %) and a minor amount of quartz and dolomite.

Table 2

The results of X-ray diffraction analysis of the core samples

Well	Sample Sr. No.	Depth, m	Stratum	Calcite	Quartz	Dolomite	Total
W-1	27	4520.6	B	99.6	0.4	0	100
	40	4522.6	B	99.6	0.4	0	100
	52	4524.6	B	99	1.0	0	100
	72	4527	B	99.3	0.7	0	100
	84	4528.4	B	99.6	0.4	0	100
	91	4530.2	B	99.4	0.6	0	100
	164	4600.9	B	99.5	0.5	0	100
	181	4605.1	B	99.5	0.5	0	100
	192	4606.3	D	99.3	0.7	0	100
	200	4607.4	D	99.5	0.5	0	100
W-2	5	4581.5	D	95.6	0.4	4	100
	10	4582.7	D	99.5	0.5	0	100
	11	4582.8	D	99.5	0.5	0	100
	17	4583.4	D	99.6	0.4	0	100
	47	4586.8	D	99.5	0.5	0	100
	58	4589.3	D	99.6	0.4	0	100
	70	4590.6	D	99.6	0.4	0	100
W-3	56	4601.1	D	99.1	0.9	0	100

To assess the influence of the acid concentration and injection rate on the wormhole formation, the samples were selected the way to describe average parameters of the two main strata, as per Table 3.

After the main parameters were measured, the sample was saturated with formation water to 100 % using a saturator. Then, to obtain residual water saturation, it was saturated with an artificial oil sample with viscosity equivalent to the formation oil, at the formation temperature and pressure, using an ultracentrifuge. Afterwards, the sample was placed into the testing apparatus and tested in the conditions replicating those in the formation: overburden pressure – 1098.94 atm; pore pressure – 501.7 atm; effective pressure – 597.24 atm; oil viscosity – 0.37 cP; oil viscosity – 0.569 cP; formation temperature – 120 °C.

Testing to assess the acid concentration influence on wormhole formation

Prior to the acid injection, the effective permeability to oil was assessed.

During the injection, the pressure differential between sample entry and exit was measured. The injection of acid with various concentrations was performed with the flow rate of 1 cm^3/min until a wormhole breakthrough (a rapid pressure differential decline). The injected acid volume was captured at the time of the wormhole breakthrough. Next, 2L distilled water was pumped through the sample at a flow rate of 1 cm^3/min. After the experiment, the samples were inspected visually (with taking photographs) and analysed using micro-CT. An example the test is shown in Figure 4, *a*.

A total of three tests were performed for each stratum (B and D) with various acid concentrations (5, 10 and 15 %). The test results are shown in Table 4.

The comparison of the obtained wormhole structures is provided in Figure 5.

Testing results suggest that acid concentration influences the development of wormholes. At injection rate of 1 cm^3/min, the most optimum wormhole structure (long, weakly ramified, requiring a minimum volume of the injected acid compound) is formed in response to injection of 5 % acid, with minimum acid volume consumed (about 1.0–1.2 cm^3 in 15 % acid equivalent). On the other hand, the total volume of the injected solution is minimal. The problem of acid concentration influence on the development of wormholes requires further study; specifically, it is necessary to look into the impact of injection rate at various acid concentrations.

Table 3

The basic parameters of the core samples selected
for studying the acid treatment effectiveness

Sample Sr. No.	Depth, m	Stratum	Length, cm	Sample volume, cm^3	Pore volume, cm3	Porosity, %	Rock matrix density, g/cm^3	Permeability to gas, md
88	4528.97	B	3.83	42.70	5.89	13.80	2.69	2.65
90	4530.15	B	3.51	38.98	6.03	15.50	2.69	2.75
102	4532.24	B	3.59	39.77	5.31	13.30	2.69	3.38
124	4596.37	D	3.19	35.49	5.53	15.60	2.68	7.25
131	4597.45	D	3.36	36.36	5.93	16.30	2.68	9.14
135	4597.78	D	3.46	38.26	6.31	16.50	2.69	10.10
58	4525.09	B	3.30	36.85	6.25	17.00	2.69	3.39
60	4525.2	B	3.86	42.93	7.00	16.30	2.70	2.94
62	4525.43	B	3.53	39.14	6.88	17.60	2.70	3.69
73	4527.04	B	3.51	39.09	5.60	14.30	2.70	2.52
74	4527.18	B	3.27	36.18	5.61	15.50	2.70	3.59
105	4594.23	D	3.35	37.30	6.25	16.80	2.68	8.65
112	4595.2	D	3.11	34.57	5.68	16.40	2.68	9.92
115	4595.58	D	3.23	35.96	6.01	16.70	2.69	8.15
118	4595.86	D	3.16	35.09	6.01	17.10	2.68	10.60
128	4596.81	D	3.39	37.66	6.00	15.90	2.68	11.10

Table 4

The summary results of the experiments to assess the injected acid concentration influence on the wormhole development

Sample Sr. No.	Stratum	Acid concentration, %	Effective permeability to oil, md	Injection rate, cm/min	Injected acid volume to wormhole breakthrough, cm^3	Time to wormhole breakthrough, s	15% acid volume equivalent, cm^3
88	B	5	1.03	0.090	3.50	210	1.167
90	B	10	0.98	0.090	2.50	150	1.667
102	B	15	1.10	0.090	2.00	120	2.000
124	D	5	3.64	0.090	3.00	180	1.000
131	D	10	3.61	0.092	2.25	135	1.500
135	D	15	3.79	1.00	1.50	90	1.500

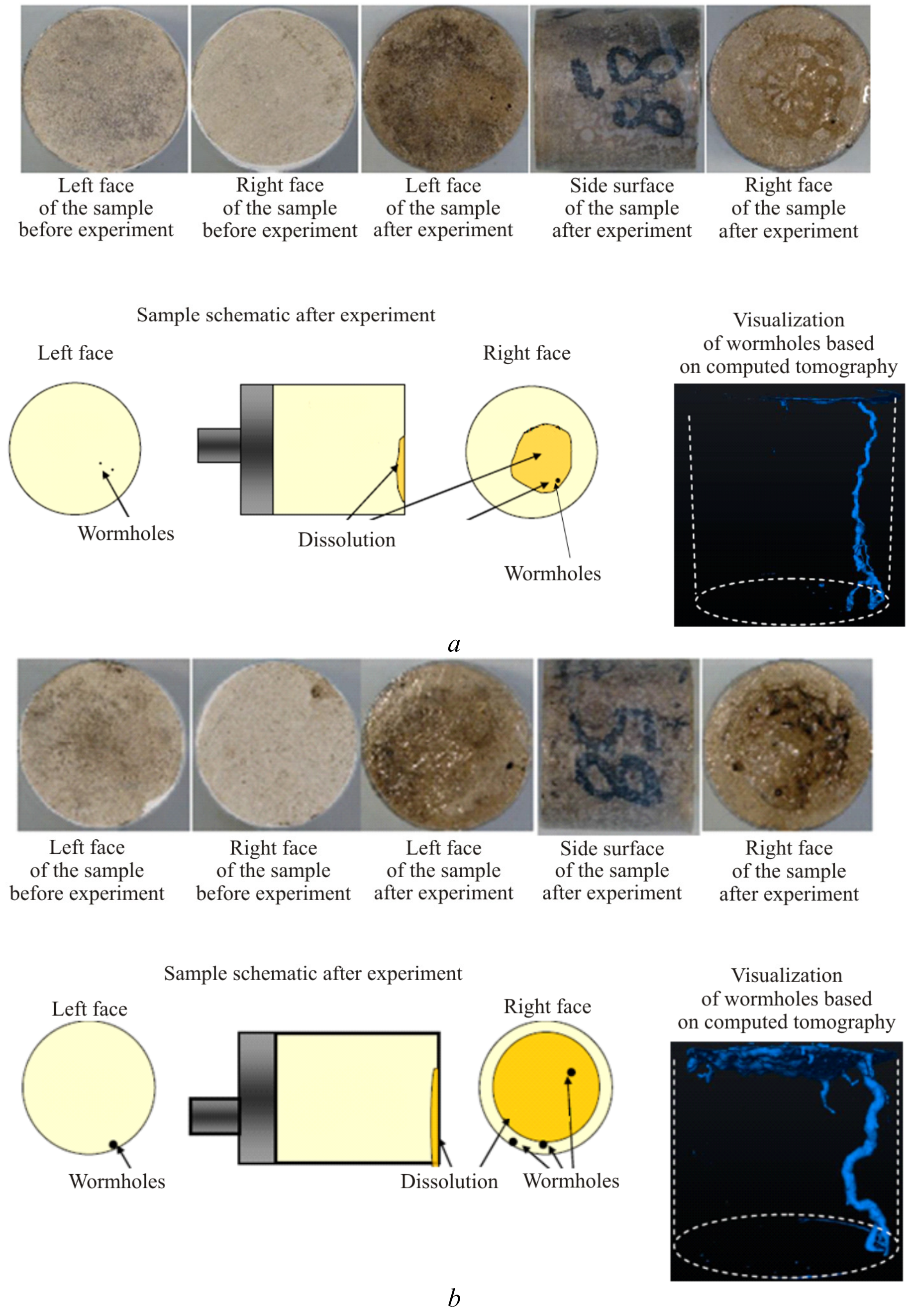
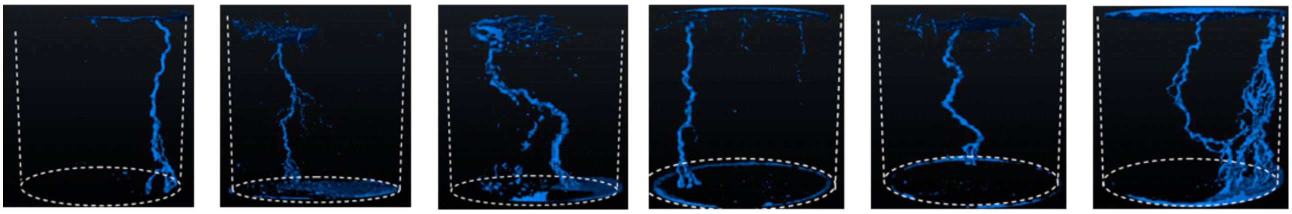


Fig. 4. The results of the experiment to assess the influence on the wormhole development: *a* – 5% acid concentration (sample No. 88); *b* – 15% acid injection rate (sample No. 58, flow rate – 0.2 cm^3/min)



Sample 88, 5 % HCl | Sample 90, 10 % HCl | Sample 102, 15 % HCl | Sample 124, 5 % HCl | Sample 131, 10 % HCl | Sample 135, 15 % HCl

Fig. 5. Comparison of wormhole development structures depending on injected acid concentration

Table 5

The summary results of the experiments to assess the 15% acid injection rate influence on the wormhole development

Sample Sr. No.	Stratum	Effective permeability to oil at residual water saturation, md	Injection rate, cm/min	Injected acid volume to wormhole breakthrough, cm^3	Time to wormhole breakthrough, s
60	B	0.92	0.045	5.75	690
62	B	1.34	0.090	2.30	138
73	B	0.90	0.449	2.50	30
74	B	1.16	0.904	2.50	15
102	B	1.10	0.090	2.00	120
112	D	4.36	0.045	3.50	420
115	D	3.81	0.090	2.00	120
118	D	5.36	0.450	4.20	50.4
128	D	5.45	0.900	3.00	18
135	D	3.79	0.090	1.50	90

Testing to assess the acid injection rate influence on wormhole formation

The tests were conducted at formation conditions. During injection, the pressure differential between sample entry and exit was measured. Injection of acid with the most commonly used concentration of 15 % was performed at different flow rates until a wormhole breakthrough (rapid pressure differential decline). Injected acid volume was captured at the time of the wormhole breakthrough. Next, 2L distilled water was pumped through the sample at the same flow rate as the acid injection. After the experiment, the samples were inspected visually (with taking photographs) and analysed using micro-CT. An example of the test is shown in Figure 4, *b*.

A total of five tests were performed for each stratum (B and D). The test results are shown in Table 5.

Figure 6 illustrates the comparison of the obtained wormhole structures.

The results of the study suggest that the acid injection rate influences the development of wormholes. The most optimum structure (long weakly ramified wormholes produced at the minimum injected acid compound volume) is formed in response to the injection of acid with the injection rate of about 0.6 cm/min (Figure 7). The experiment results for both strata can be described using the same dependency of the injected acid *PVBT* on the injection rate.

The obtained optimum injection rate values and their corresponding injected acid volumes were used to design a HAT at producing wells in the acid treatment model developed by the authors of the paper. It helped achieve an average skin factor for the producing wells (4.7) and productive thickness sweep up to 95 %. The practical examples of using and modelling details are provided in [66].

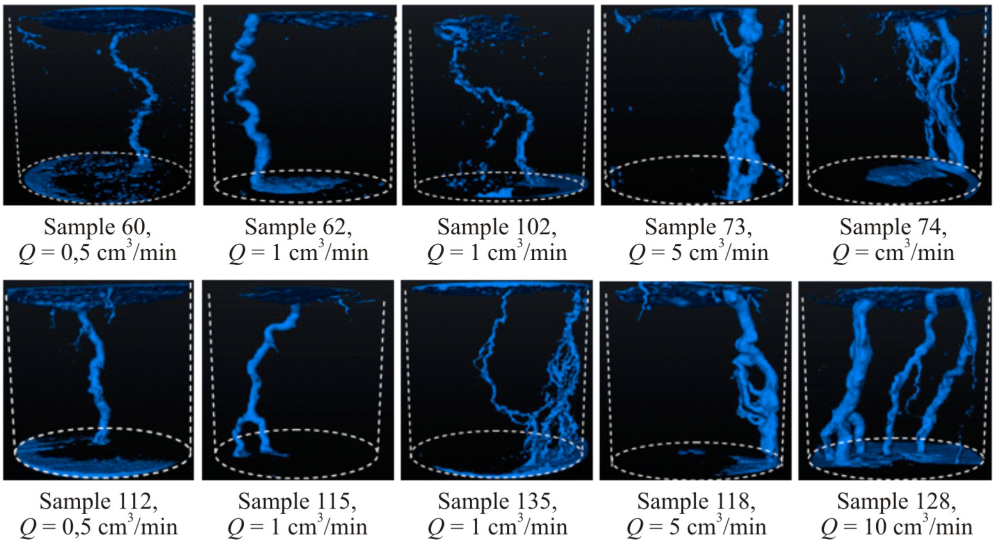

Sample 60, $Q = 0{,}5$ cm^3/min
Sample 62, $Q = 1$ cm^3/min
Sample 102, $Q = 1$ cm^3/min
Sample 73, $Q = 5$ cm^3/min
Sample 74, $Q =$ cm^3/min
Sample 112, $Q = 0{,}5$ cm^3/min
Sample 115, $Q = 1$ cm^3/min
Sample 135, $Q = 1$ cm^3/min
Sample 118, $Q = 5$ cm^3/min
Sample 128, $Q = 10$ cm^3/min

Fig. 6. The comparison of wormhole development structures depending on the 15% acid injection rate

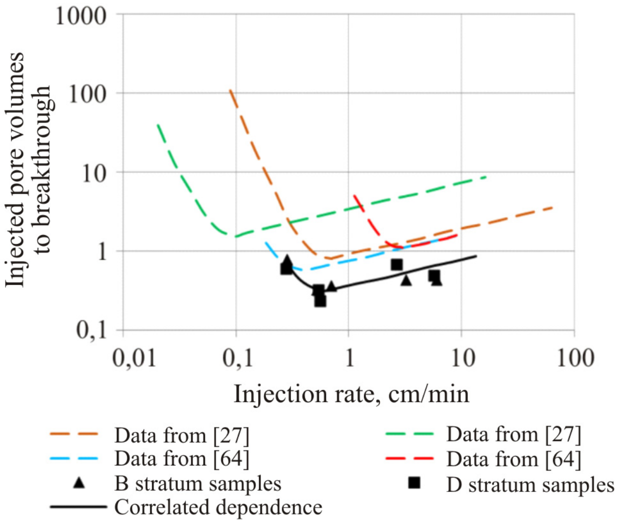


Fig. 7. Result of comparison of the performed experiments (black curve) and data provided in [27, 64]

Conclusions

1. Multiple instances of research have shown that any given rock-acid compound system has an optimum injection rate that helps form long weakly ramified flow channels (wormholes) at a minimum acid injection volume (*PVBT*).

2. The shape and penetration depth of wormholes are influenced by many factors, such as acid solution composition, mineral composition of the rock, formation saturation, rock inhomogeneity, injection rate, well completion type, etc.

3. The factors produce cumulative and at times divergent influence on the acid treatment effectiveness. To obtain the results that can be put into practice, it is necessary to perform tests on the samples selected in the specific field, saturated with fluids that are expected in the NWFR during the HAT, using the solutions planned for injection, at pressure and temperature values expected during the HAT.

4. In order to design a HAT for an Iraqi field, the tests have been performed to assess the influence of the acid concentration and injection rate on the acid treatment effectiveness in the conditions approximating to those expected during the HAT.

5. At a linear injection rate of 0.5 cm/min, the most optimum wormhole structure for the conditions of the field under study is formed at a low acid concentration.

6. The optimum 15% hydrochloric acid injection rate for the tested samples amounted to 0.6 cm/min.

7. The obtained results have been successfully used for HAT design in 19 wells as the input data for the acid treatment modelling.

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