ГЕОМЕХАНИКА. РАЗРУШЕНИЕ ГОРНЫХ ПОРОД. ФИЗИЧЕСКИЕ И ХИМИЧЕСКИЕ ПРОЦЕССЫ ГОРНОГО ПРОИЗВОДСТВА

DOI: 10.21440/0536-1028-2021-4-24-30

Modeling acidizing of carbonate formations with different reservoir properties

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Abstract

Introduction. *The efficiency of matrix acidizing of the bottom-hole formation zone depends on many factors, the chief being the reservoir properties.*
The research aim *is to assess the effect produced by the formation reservoir properties on the result of hydrochloric acid treatment. Experiments simulating carbonate formation acid treatment were carried out.*
Methods. *The experiments were carried out using the UIK-1 core analysis apparatus. Carbonate cores with different porosity and permeability were selected. Some of the experiments modeled permeability reduction as a result of bottom-hole formation zone contamination with drilling mud.*
Results. *The research has shown that during low permeability reservoirs acidizing, permeability increases to a greater extent than during high permeability cores acidizing. In low permeability cores, the acid solution mainly forms new channels, while in high permeability cores the expansion of existing ones mainly occurs. In the present paper, the equivalent surface area of the acid-formed channels was estimated. When acidizing low permeability cores, the equivalent area of the channels is larger than when acidizing high permeability cores. The outcome of acidizing of the core samples with impaired porosity and permeability and contaminated with model drilling mud is comparable to acidizing of low permeability samples not contaminated with drilling mud.*
Conclusions. *Acidizing of low permeability reservoirs leads to a greater increase in permeability. The equivalent area of acid-formed channels is larger than that of high permeability cores treatment. This reveals that the impact of acid on low permeability reservoirs is more effective.*

Keywords: *matrix acidizing; Damkeller number; channel surface area; permeability; reaction rate.*

Introduction. The main process occurring at well bottom-hole zone acidizing is the dissolution of reservoir carbonates. Penetrating reservoir pores, acid expands them and forms long narrow wormholes. The main outcome of matrix acidizing is the improved permeability of channels and microcracks in the bottom-hole zone of wells. This raises oil and gas wells productivity.

The latest researches in the field of well acidizing are mainly focused on assessing and analysing the mechanism of acid reaction with carbonates in-situ. Those researches analysed the impact of acid solutions injection rate on rock properties, observed the structures of channels formation, and determined the optimal injected amount and other parameters [1–12].

The original state of the bottom-hole formation zone influences significantly the efficiency of acidizing. Initial permeability, formation fluid properties, permeability volume, and the level of contamination with drilling mud are important properties. Several experiments were carried out to determine the impact of permeability on acidizing efficiency.

Methods. The experiments were carried out using a constant flow installation adapted for hydrochloric acid solutions. Solution tanks and tubes were made of stainless steel. Digital differential pressure manometers controlled pressure during liquid filtration. An automatic burette was used to measure the volume of liquid traversing the sample and prevent acid ejection. The hydro confining pressure of 10–20 MPa was maintained.

Table 1. Design of experiment
Таблица 1. План эксперимента

Experiment no.	Porosity	Permeability, μm²	Fluid that saturates the sample	Simulating contamination with drilling mud	Sample type
1	0.080	0.07	Formation water	+	–
2	0.080	0.28	Oil	+	–
3	0.090	1.50	Formation water	–	High permeability
4	0.070	0.20	Formation water	–	Low permeability
5	0.010	1.62	Oil	–	High permeability
6	0.060	0.15	Oil	–	Low permeability

Six experiments were carried out on displacing formation fluids out of the core samples with the carbonate content of 80–100%. Experiments 1 and 2 initially simulated contamination with model drilling mud based on 0.15% polyacrylamide solution (PAM). After that core sample no. 1 was saturated with formation water, while core sample no. 2 was saturated with oil. Then an acid solution was pumped through both samples up to ejection.

During experiments 3 and 5 high permeability samples were saturated with formation water and oil correspondingly. In experiments 4 and 6 low permeability core samples were saturated with formation water and oil correspondingly. Acid solution was then pumped through all samples. The design of experiment is presented in table 1.

NaCl solution with a density of 1100 kg/m^3 (experiments 1, 3, and 4) was used as model formation water. Kerosene with a density of 796 kg/m^3 and a viscosity of 1.24 MPa · s was used as model oil (experiments 2, 5, and 6).

All liquids were pumped in one direction. Due to the small size of the core samples, the change in permeability slightly depends on the direction of filtration.

Results. In experiments 1 and 2, hydrodynamic mobility was determined by filtering about 3 pore volumes of formation fluid through the samples with constant speed until stabilization. After that, not less than 3 pore volumes of model drilling mud were pumped. In all the experiments, constant filtration speed was maintained; fluid flow rate was 0.135 cm^3/min. Then hydrochloric acid (12%) was injected until the samples developed an end-to-end channel. According to Darcy's law and the obtained data, the hydrodynamic mobility k/μ was determined.

In experiments 3 and 5, high permeability core samples were used. Into sample no. 3 model formation water was injected, while into sample no. 5 model oil was injected. After that the acid solution pumped in. Experiments 4 and 6 were carried out similarly to experiments 3 and 5 but with the use of low permeability core samples.

Under the condition of core samples contamination with model drilling mud, the hydrodynamic mobility fell by more than 10 times as compared to the initial value. It is due to filtration channels diameter reduction as a result of polymeric structures adsorption on the surface of channels and pores which reduce the hydrodynamic mobility.

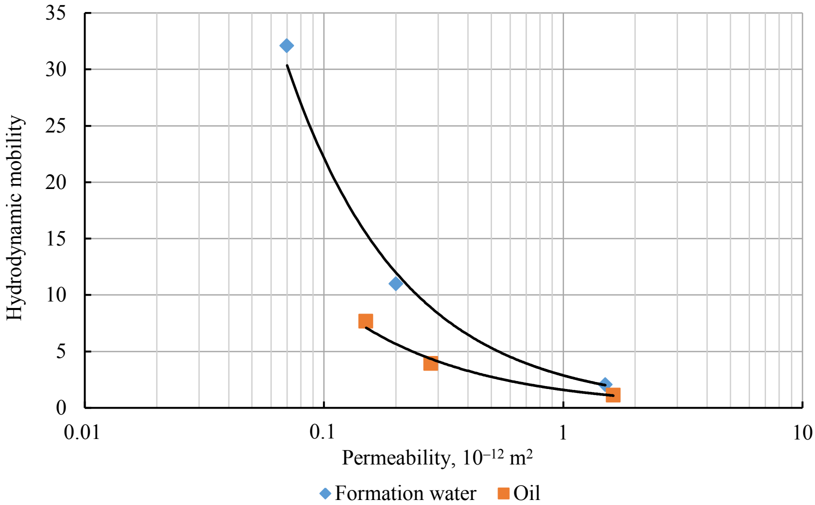

Fig. 1. Hydrodynamic mobility change
Рис. 1. Изменение гидродинамической подвижности

Mobility reduction simulates temporary insulation of the formation when it is contaminated with drilling mud. Recovery and permeability improvement of the core samples were carried out with the hydrochloric acid solution. As the acid solution was

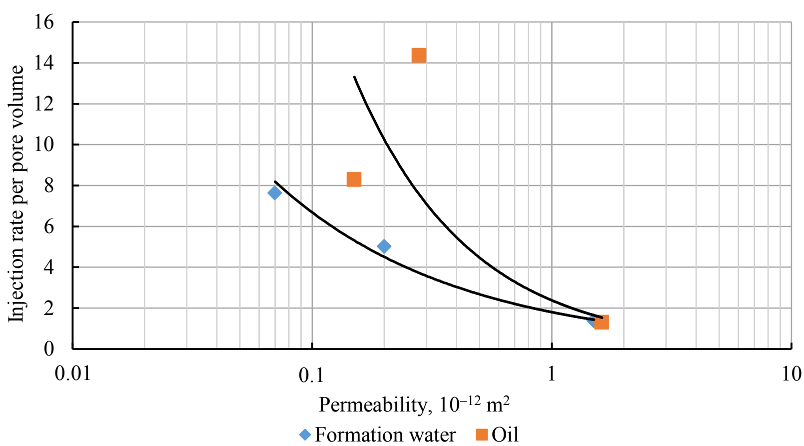

Fig. 2. Acid solution volume before it is pumped through the sample
Рис. 2. Объем кислотного раствора до прорыва кислоты сквозь образец

injected, the hydrodynamic mobility increased. After having injected several pore volumes of acid, the hydrodynamic mobility increased significantly as a result of the end-to-end channel development.

Analysis and discussion. From the experimental results, the efficiency of hydrodynamic mobility recovery by hydrochloric acid treatment was assessed. As can be seen in fig. 1, the lower the value of the initial permeability, the more intensively the hydrodynamic mobility increases under acidizing. It does not depend on whether the core permeability was originally low or it was reduced due to contamination with drilling mud.

Table 2. Channels surface area
Таблица 2. Площадь поверхности каналов

Experiment no.	V/V_{pore}	$1/Da$	Da	S, cm^2
1	7.63	0.43	2.3300	1.374
2	14.36	0.38	2.6300	1.704
3	1.38	0.68	1.4788	0.216
4	5.02	0.48	2.0800	0.495
5	1.30	0.74	1.3500	0.190
6	8.29	0.46	2.1700	0.516

It is also noted that in water-saturated cores, the effect of hydrodynamic mobility increase is stronger than in oil-saturated cores. It is due to the different character of liquids wettability in a porous medium.

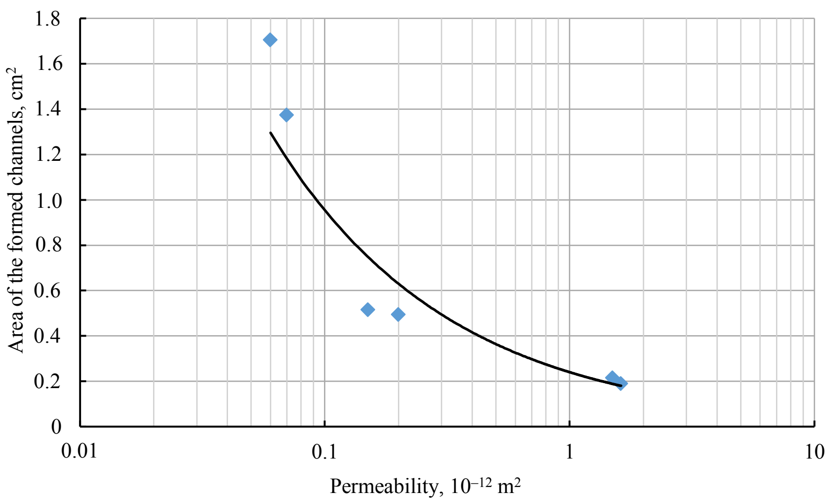

Fig. 3. Dependence between end-to-end channels surface area and permeability
Рис. 3. Площадь поверхности сквозных каналов

The efficiency of acidizing was also assessed by the injection rate per pore volume of acid solution to create end-to-end channels. Works [9, 10] were the first to direct attention to that. It can be seen from the experimental results that when treating the low-permeability samples, end-to-end channels develop under the larger injection rate per pore volume of acid solution injection, which promotes reservoirs deep processing (fig. 2).

In works [8–10], the dependence between the injection rate per pore volume (V/V_{pore}) and the Damkeller number was determined. It is described by equation:

$$Da = \frac{Sk}{Q},$$

where S is the equivalent area of channels surface, cm^2; k is the constant of the chemical reaction rate, cm/min; Q is the acid feed rate, cm^3/min.

To assess the equivalent area of the end-to-end channels, the Damkeller ratio can be used. Based on the injection rate per pore volume of the injected acid solution until the development of an end-to-end channel, for each experiment, the Damkeller number and the equivalent area of channels surface were determined. The results are presented in table 2 and fig. 3.

As can be seen from fig. 3, the end-to-end channels which have been developed in the low permeability samples, possess a large equivalent area. It is related to the fact that there is some correlation between the permeability and the diameter of the pore channels. The diameter of the high permeability samples is larger, therefore in high permeability formations the major part of the acid solution is consumed to extend the existing pore channels, while the formation of the new ones is less effective as compared to the low permeability formations [10].

Summary. Reservoir properties of the low permeability core samples were improved greater than of initially high permeability cores, under otherwise equal conditions. Low permeability formations acidizing requires a relatively large amount of hydrochloric acid solution. It is because the acid volume is mainly consumed to develop new channels rather than extend the existing ones. The equivalent area makes it possible to assess the efficiency of acidizing and the development of end-to-end channels. In low permeability samples, the equivalent area of channels is significantly larger proving high efficiency of low permeability formations acidizing.

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Received 28 December 2020

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УДК 622.276.63 DOI: 10.21440/0536-1028-2021-4-24-30

Моделирование кислотной обработки карбонатных пластов с разными коллекторскими свойствами

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Реферат
Введение. *Эффективность кислотной обработки призабойной зоны пласта зависит от многих факторов, главными из которых являются фильтрационно-емкостные свойства пласта.*
Цель. *Оценка влияния фильтрационно-емкостных свойств пласта на результат соляно-кислотной обработки. Для этого проведены опыты, моделирующие процесс кислотной обработки пласта.*
Методы. *Опыты проводились на установке исследования керна УИК-1. Для исследования были выбраны карбонатные керны с различными фильтрационно-емкостными свойствами. Часть опытов проводилась с моделированием ухудшения проницаемости вследствие загрязнения призабойной зоны пласта буровым раствором.*
Результаты. *В результате проведенных опытов определено, что увеличение проницаемости при кислотной обработке низкопроницаемых коллекторов происходит в большей степени, чем при обработке высокопроницаемых кернов. В низкопроницаемых кернах кислотный раствор преимущественно образовывает новые каналы, тогда как в высокопроницаемых в основном происходит расширение уже существующих. В ходе работы оценена эквивалентная площадь поверхности каналов, сформированных кислотным раствором. При обработке низкопроницаемых кернов эквивалентная площадь каналов больше, чем при кислотном воздействии на высокопроницаемые керны. Кислотная обработка кернов с ухудшенными фильтрационно-емкостными свойствами при загрязнении моделью бурового раствора имеет результат, сопоставимый с обработкой низкопроницаемых образцов, не загрязненных буровым раствором.*
Выводы. *При кислотной обработке низкопроницаемых коллекторов происходит увеличение проницаемости в большей степени, и эквивалентная площадь каналов, образованных кислотным раствором, больше в сравнении с аналогичными показателями при обработке высокопроницаемых кернов, что показывает более высокую эффективность кислотного воздействия на низкопроницаемые коллекторы.*

Ключевые слова: *кислотная обработка; число Дамкеллера; площадь каналов; проницаемость; скорость реакции.*

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Поступила в редакцию 28 декабря 2020 года

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Для цитирования: Дорфман М. Б., Сентемов А. А. Моделирование кислотной обработки карбонатных пластов с разными коллекторскими свойствами // Известия вузов. Горный журнал. 2021. № 4. С. 24–30 (In Eng.). DOI: 10.21440/0536-1028-2021-4-24-30

For citation: Dorfman M. B., Sentemov A. A. Modeling acidizing of carbonate formations with different reservoir properties. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal = News of the Higher Institutions. Mining Journal*. 2021; 4: 24–30. DOI: 10.21440/0536-1028-2021-4-24-30