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Study of wormhole channel formation resulting from hydrochloric acid treatment in complex-type reservoirs using filtration and X-ray computed tomography methods

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Abstract
The primary function of hydrochloric acid treatment (HAT) is to create the maximum number of high-conductivity channels in the near-wellbore zone of the reservoir to restore its permeability and enhance hydraulic connectivity between the undisturbed part of the formation and the well. The objective of this study is to physically model HAT on core samples from the Orenburg oil and gas condensate field and to research the impact of such treatment on the structure of the pore space of rocks related to complex-type reservoirs. The complexity of the rock's pore space and the low permeability of the formations are distinguishing features of the study object. For this reason, HAT is a widely applied method for production intensification, necessitating the verification of acid injection rates, where the success criterion is the formation of high-conductivity filtration channels (wormholes) in the near-wellbore zone. These channels significantly expand the drainage area of wells, thereby bringing additional reservoir sections into development. The study examined the characteristics of filtration channel development resulting from acid treatment. Their structure was characterized and analyzed using X-ray computed tomography. The complex study confirmed the accuracy of the selected injection rate and provided practical recommendations for enhancing the efficiency of HAT.

Keywords
X-ray tomography; hydrochloric acid treatment; pore space; reservoir properties; carbonate reservoir; wormhole

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Introduction

There is a trend towards a decline in hydrocarbon (HC) production from terrigenous reservoirs and the development of carbonate deposits, which are characterized by low reservoir properties (RP) and complex pore space structures. The process of HC extraction from such reservoirs is more labor-intensive and economically costly than from traditional reservoirs. To ensure successful field development in such conditions, various geological and technical measures are carried out to increase the efficiency of oil and gas production and accelerate the production rates of recoverable reserves [1-3].

Chemical methods are most commonly used for carbonate reservoirs, particularly hydrochloric acid treatment (HAT), which is one of the main methods for enhancing oil production. The technology was developed by chief chemist Herman Frasch, who worked at a Standard Oil refinery in Ohio, USA, and patented the method in 1896 [4]. Since then, the method has been actively used in the oil and gas industry, and currently, there are numerous variations depending on the acid composition [5-7] and treatment technology [8-10]. During HAT, the acid dissolves the solid phase and creates deep, highly permeable channels with a wormhole-like structure [11-13]. Some studies have

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shown that wormholes can form even at very low acid concentrations, which may indicate their deep penetration into the reservoir [14, 15].

Most foreign publications focus on mathematical modeling of acid treatment, while the work of domestic researchers is primarily directed towards service support for acidizing operations. There are only a few publications dedicated to studying the processes and mechanisms occurring during the interaction of reservoir rock with acid solutions, which is a fundamental factor for proper planning of the treatment and maximizing its effectiveness. Laboratory core studies are the only foundation that provides preliminary insights into the research object and the processes occurring in the rock. The majority of theoretical and experimental research is focused on determining the regimes of acid treatment and the composition of acid mixtures for more effective rock dissolution and treatment. For example, in the article [16] the results of studies on selecting the acid composition for treatment of the near-wellbore zone in low-permeability terrigenous reservoir rocks of Jurassic deposits are presented. It was found that a two-stage treatment of core material, first with hydrochloric acid and then with clay-acid compositions, is the most effective. In another study [17] the process of secondary precipitate formation during acid treatment in terrigenous reservoirs of Western Siberia is studied in more detail. To prevent its formation, based on the results of experiments, it is recommended to strictly control the contact time between the acid composition and the reservoir rock, as well as to use modifying additives that affect the surfactant properties of the acid compositions. A similar issue was addressed in the study for reservoirs with high temperatures [18], where the process of pre-flushing the well is proposed as one of the most effective stages of acid treatment for oil wells, significantly reducing the issue of secondary precipitate formation. The pre-flushing stage cools the rock surface and reduces the acid's reaction rate with the rock at high reservoir temperatures.

There is a growing number of publications dedicated to the topic of modeling hydrochloric acid treatment at the pore level [19-21]. For example, in the article [19] the results of a developed mathematical model for simulating acid treatment using X-ray computed tomography data are presented. The research focused on core samples from a carbonate reservoir of Cretaceous deposits. The simulation of acid treatment at different injection rates demonstrated the heterogeneous nature of the dissolution process, leading to wormhole formation within a specific range of injection rates.

Acid treatment simulation is also conducted at a higher level – for reservoirs and fields – using acidizing simulators. In the study [22] for polymictic reservoirs in Western Siberia, a series of calculations were performed within the framework of improving the effectiveness of near-wellbore zone treatment using clay-acid compositions. These calculations were aimed at determining the optimal volume of acid composition injection, and recommendations were provided for enhancing the efficiency of acid treatment. In the article [23] the problem of mathematical modeling of acid treatment on the near-wellbore zone (NWZ) of gas fields with carbonate fractured-porous reservoirs is discussed. Based on the proposed model, the progression of the acid and the change in the filtration characteristics of the bottom-hole formation zone (BFZ) were studied during acid injection under various regimes. In the article [24] a model of multiple acid treatments is presented, taking into account the complex structure of the NWZ, combining submodels of the wellbore, pressure and flow rate calculations, fluid distribution in the NWZ, wormhole development, skin factor calculation, and the consideration of flow diverters.

A significantly smaller number of studies are dedicated to exploring the impact of acid treatment on the pore space and reservoir properties of real carbonate rocks. In the study [25] a comparison of the impact of acid treatment on high- and low-permeability carbonate reservoirs was conducted. The results of acid treatment on core samples showed that, when treating low-permeability samples, the equivalent dissolution channel area was larger than with acid treatment on high-permeability samples, indicating higher effectiveness of acid treatment on low-permeability reservoirs. In the study [26] the

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effect of hydrochloric acid concentration on the pore size distribution of core samples from a carbonate reservoir and its reservoir properties was studied. It was found that the use of 15 % hydrochloric acid leads to an increase in porosity, in some cases up to 2.5 times, and the median pore diameter Md_p increases up to three times. In the article [27] the effect of self-diverting acid compositions on reservoir properties and the channels formed as a result of acid treatment was studied. The effect of forming a network of etched channels through the injection of self-diverting acid compositions was demonstrated. It was found that the use of such compositions reduces the acid penetration rate, which can later ensure more uniform treatment.

Even fewer studies are dedicated to exploring the structure of the formed wormholes, particularly in samples belonging to complex reservoir types [28-30]. It is necessary to study in more detail the process of hydrochloric acid treatment on rock samples to improve the effectiveness of acidizing. This need has defined the objective of the present study – to analyze the changes in the structure of the pore space of rocks belonging to a complex reservoir type under the influence of acid treatment, using the productive section of the Orenburg oil and gas condensate field (OGCF) as an example, with the application of X-ray computed tomography and laboratory core studies. The specific feature of the research object is the complexity of the pore structure of the rocks and the low permeability of the reservoirs. Since acid treatment is a widely applied method for enhancing production, there is a need for direct verification of the justification for the acid injection rates used, with the success criterion being the formation of highly conductive filtration channels (wormholes) in the near-wellbore zone, which significantly expand the drainage area of wells and, thereby, involve additional areas of the reservoir in the development.

Objects and methods

The work utilized samples of real reservoir rocks of the pore-cavernous and fractured types, which are most characteristic for the Eastern section of the Orenburg oil and gas condensate field. Sample KP-01 represents an organic-detrital limestone with thin (up to 1 mm) lenses of bituminous material oriented across the core axis. The detritus in the limestone consists of shell fragments of brachiopods, gastropods, and crinoids, ranging from 0.2 to 1.5 mm, cemented with fine-grained calcite and dolomite. The cement type is basaltic-pore, porous. Sample T-02 represents a chemogenic limestone with inclusions of rounded faunal fragments up to 0.5 mm, dolomitic, and sulfated. Two stylolitic seams are observed, oriented across the core axis, filled with clayey-bituminous material. The fractures in the sample are weakly undulating, rarely branching, sometimes with a collisional pattern, oriented subparallel to the core axis, with occasional brownish oil accumulations along them. The fracture density parameter for the core sample is 0.2 units/mm^3.

The research on these samples was conducted in several stages. The first stage involved studying the structure of the pore space using X-ray computed tomography (CT) and determining the core's filtration characteristics before acid treatment. The second stage involved the injection of hydrochloric acid solution through the core samples. The final stage included re-scanning and laboratory studies of the core after hydrochloric acid treatment.

X-ray computed tomography has been used to study the structure of the pore space of rocks since the 1980s. Today, CT is one of the developing and informative methods in the oil and gas industry, allowing for the visualization and quantitative characterization of the composition, structure of rocks, and their pore space [31-33], and is also used for modeling hydrodynamic processes occurring within the pore space [34-36]. In this study, X-ray tomographic investigations were conducted using the SkyScan 1172 computed tomography scanner (Belgium). The scanning parameters were as follows: rotation step of 0.2 deg; averaging over eight frames; rotation angle of 360 deg; X-ray tube voltage of 100 kV; current of 100 μA; and resolution of 10 μm. One of the main advantages of computed tomography is its ability to study the structure of the pore space of various types of reservoir samples without compromising their integrity, meaning the same core cylinders can be used for modeling acid treatment. During scanning, the samples were strictly spatially oriented to ensure

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accurate post-acid treatment imaging, allowing for comparisons between the studied objects and tomographic results.

On the HP-CFS setup, hydrochloric acid solution was pumped through samples KP-01 and T-02, and their filtration properties were determined before, during, and after the injection of the solution. This setup enables high-level experimentation to study fluid filtration through porous media under reservoir thermobaric conditions. It allows filtration experiments on packed porous media models and core samples at temperatures up to 150 °C. A backpressure system is used when necessary, supporting a maximum pressure of 7.0 MPa. For core sample testing, the confining pressure can reach up to 50.0 MPa. Fluid filtration is conducted at fixed flow rates of up to 600 cm^3/h. Heating of the core sample inside the core holder to the experimental temperature is achieved using a liquid thermostat.

The experiment was conducted under conditions as close as possible to real acid treatment operations in wells. A 12 % hydrochloric acid solution with the necessary inhibitors, prepared for acid treatment in one of the wells of the Orenburg oil and gas condensate field, was used for injection. The experiments were carried out at the actual reservoir temperature of 20 °C. The viscosity of the reservoir water was 1.024 mPa·s, and its density was 1.012 g/cm^3.

Results and discussion

At the first stage of the tomographic study of sample KP-01, the following findings were revealed: the pore space of the sample is represented by intercrystalline pores and caverns. The pore and cavern sizes range from 3.3 μm to 1.9 mm, with a median value of 78.65 μm. The pore density parameter Pd_p for the sample is 277 units/mm^3; the pore surface area S_p is 6138.3 mm^2/mm^3; and the porosity K_p is 10.53 %. The majority of the sample's capacity – 68.84 % – is accounted for by ellipsoidal pores, while rounded and slit-shaped pores constitute 17.74 and 13.42 %, respectively.

The tomographic analysis of sample T-02 revealed the following: the pore space is characterized by intercrystalline pores, fractures, and residual pores within a stylolite seam. The pore size ranges from 3.3 to 448 μm, with Md_p – 57.6 μm; Pd_p – 21 units/mm^3; S_p – 3.4 mm^2/mm^3; K_p – 1.07 %. Although visually the fracture on the sample and tomographic slices appears as a plane of rock continuity disruption, it is actually a system of cavities ranging from 75 to 448 μm in size with an ellipsoidal-tubular shape. Among them, 95 % of supercapillary cavities are interconnected through smaller ones. The fracture cavities differ from intercrystalline pores in the rock matrix by size, shape, and orientation. Fracture cavities are more elongated (shape coefficient 0.5-0.7 in the fracture vs. 0.7-0.8 in the matrix) and oriented along the fracture dip. Residual cavities within the stylolite seam are mostly ellipsoidal, largely isolated from each other, and exhibit weak hydrodynamic connectivity. Next, formation water was pumped through the samples until stable filtration was obtained under a pressure differential (ΔP) of 4.81 atm at the ends of sample KP-01 and 19.2 atm for sample T-02 (Fig.1). The initial permeability k_{perm} of the samples with water was 0.82 mD for KP-01 and 0.21 mD for T-02.

During the second stage, instead of formation water, technological hydrochloric acid solution was injected. The flow rate (FlR) remained constant throughout the entire experiment at 20 cm^3/h. As shown in the pressure change graph during the experiment (Fig.1), the breakthrough time of the hydrochloric acid solution through the sample, marked by a sharp decrease in FlR and a corresponding increase in permeability, was significantly different for the two types of reservoirs. For the pore-cavernous reservoir (KP-01), the breakthrough occurred in 66 min, for the fractured reservoir (T-02), it was much faster, at 17 min. The final permeability values after the acid treatment were 5902 mD and 5930 mD, respectively, demonstrating a substantial improvement in permeability for both types of collectors.

At the third stage, X-ray tomography of the core samples was performed after the HAT. The permeability values and filtration resistance of the samples clearly indicated changes in the reservoir properties of the samples, with the formation of through dissolution channels. Structural changes in the pore space of the rock samples were scanned using X-ray computed tomography, conducted under the same imaging parameters as before the injection.

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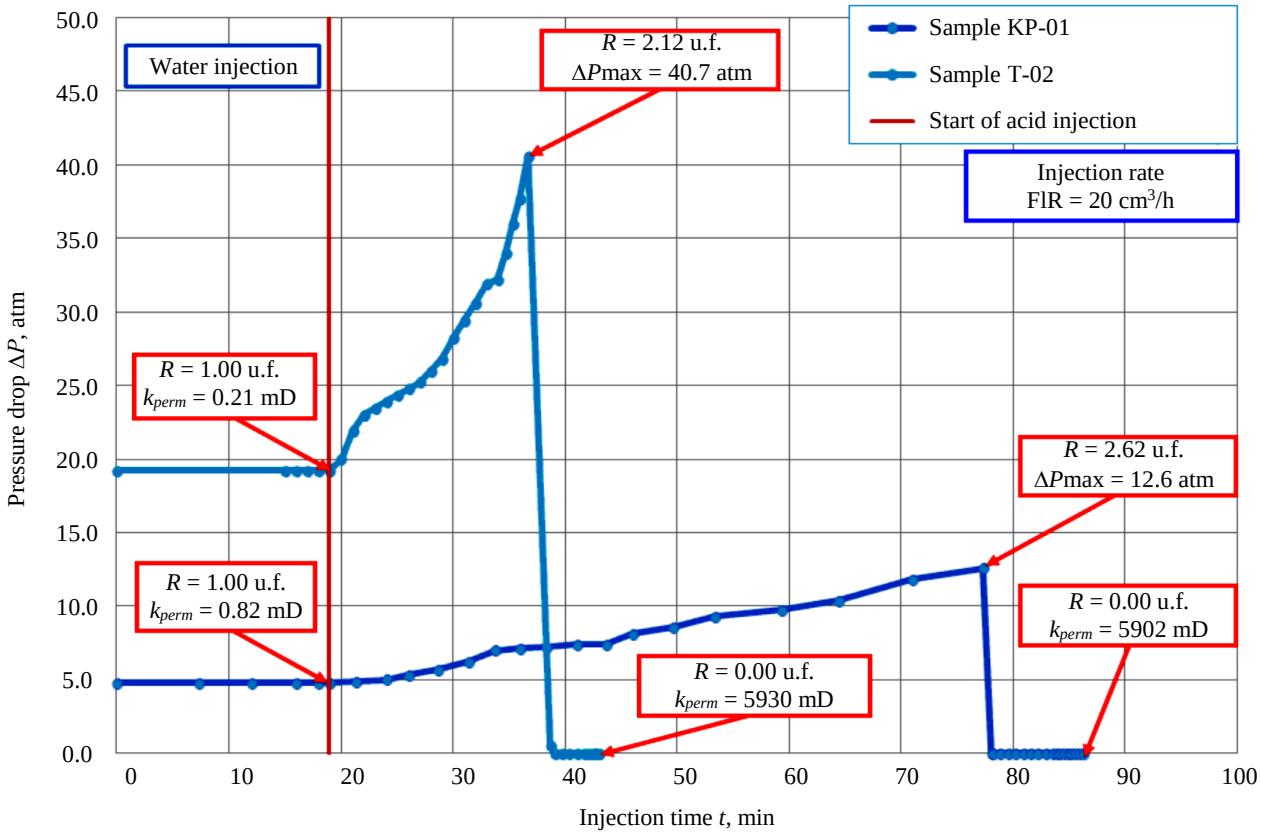


Fig.1. Pressure change characteristics during injection of technological acid solution into water-saturated core samples KP-01 and T-02

The graph in Fig.2 illustrates the changes in porosity along the entire length of the KP-01 sample and the X-ray tomography of the extended dissolution channel formed. During the acid treatment process, constant contact between the carbonate material and the acid solution was observed at the inlet end, leading to the formation of a complete dissolution segment – zone I. Further within the sample volume, zone II was formed, characterized by changes in the primary structure of the pore space due to the creation of new cavities and short channels, with a depth of 7 mm in the sample.

Fig.3 represents tomographic slices of zone II of the samples before and after HAT. For sample KP-01, significant changes in the structure of the pore space are observed in absolute values: the maximum pore and cavity sizes increased from 250 to 861 μm (3.4 times); the porosity of this zone changed from 1 to 6.53 % (6.5 times); the density parameter also increased from 233 to 379 units/mm^3 (1.6 times), and the specific void surface area grew from 62.4 to 225.5 mm^2/mm^3 (3.6 times), indicating the formation of not only large dissolution voids but also smaller ones.

Sample T-02, characterized by a fractured-type void space, initially exhibited low reservoir properties, but it is in this sample that significant changes in pore space are observed compared

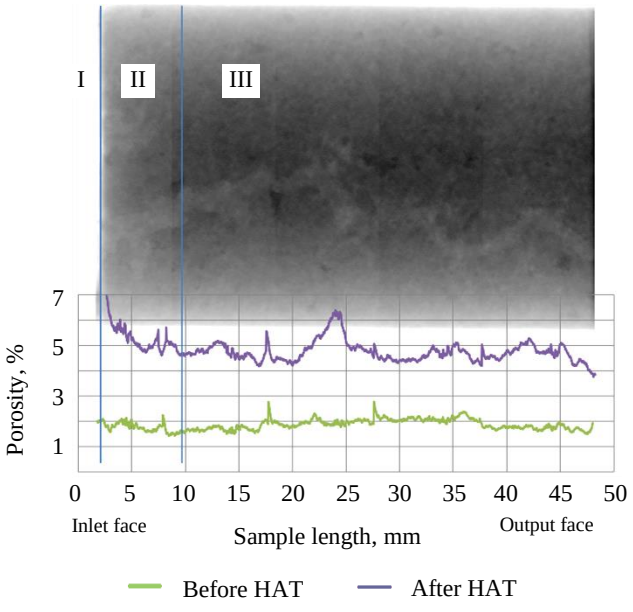


Fig.2. Graph of porosity distribution along the length of cylinder sample KP-01 before and after acid treatment

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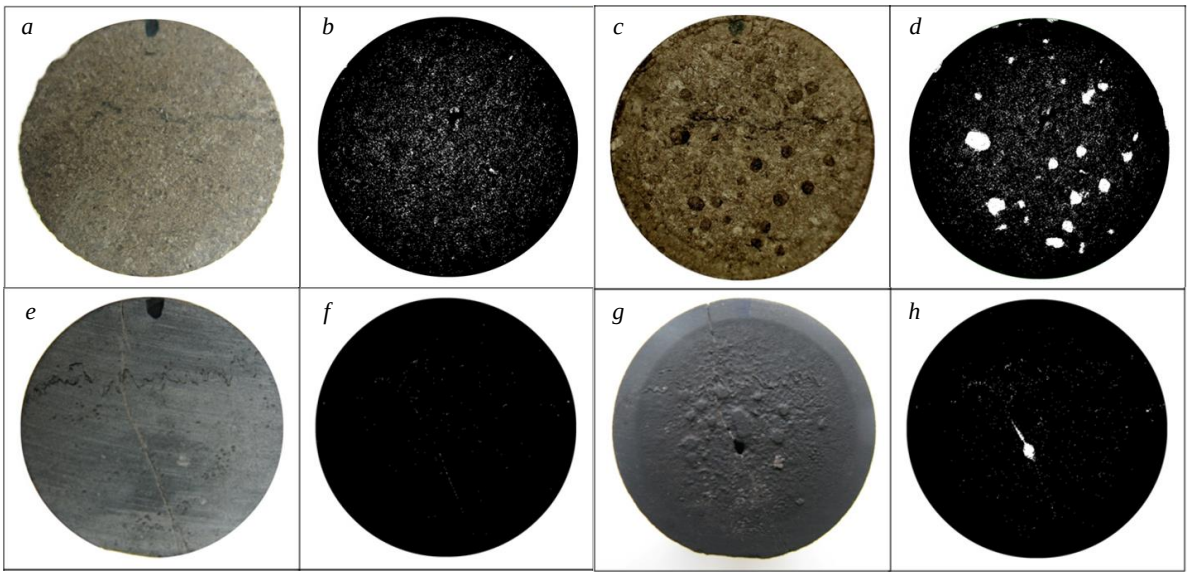


Fig.3. External view of the inlet face of sample KP-01 before (*a*) and after (*c*) HAT, and the structure of the hollow voids within it (*b*, *d*); T-02 before (*e*) and after (*g*) HAT, and the structure of the hollow voids within it (*f*, *h*): *a*, *b* – N_p = 10593 units, S_p = 62.4 mm^2/mm^3, K_p = 1.00 %, Pd_p = 233 units/mm^3, d_p : min 13.9 μm, max 249.9 μm; *c*, *d* – N_p = 17231 units, S_p = 225.53 mm^2/mm^3, K_p = 6.53 %, Pd_p = 379 units/mm^3, d_p : min 13.9 μm, max 861.7 μm; *e*, *f* – N_p = 761 units, S_p = 2.86 mm^2/mm^3, K_p = 0.04 %, Pd_p = 18 units/mm^3, d_p : min 13.9 μm, max 129.0 μm; *g*, *h* – N_p = 2828 units, S_p = 17.40 mm^2/mm^3, K_p = 0.45 %, Pd_p = 65 units/mm^3, d_p : min 13.9 μm, max 566.9 μm

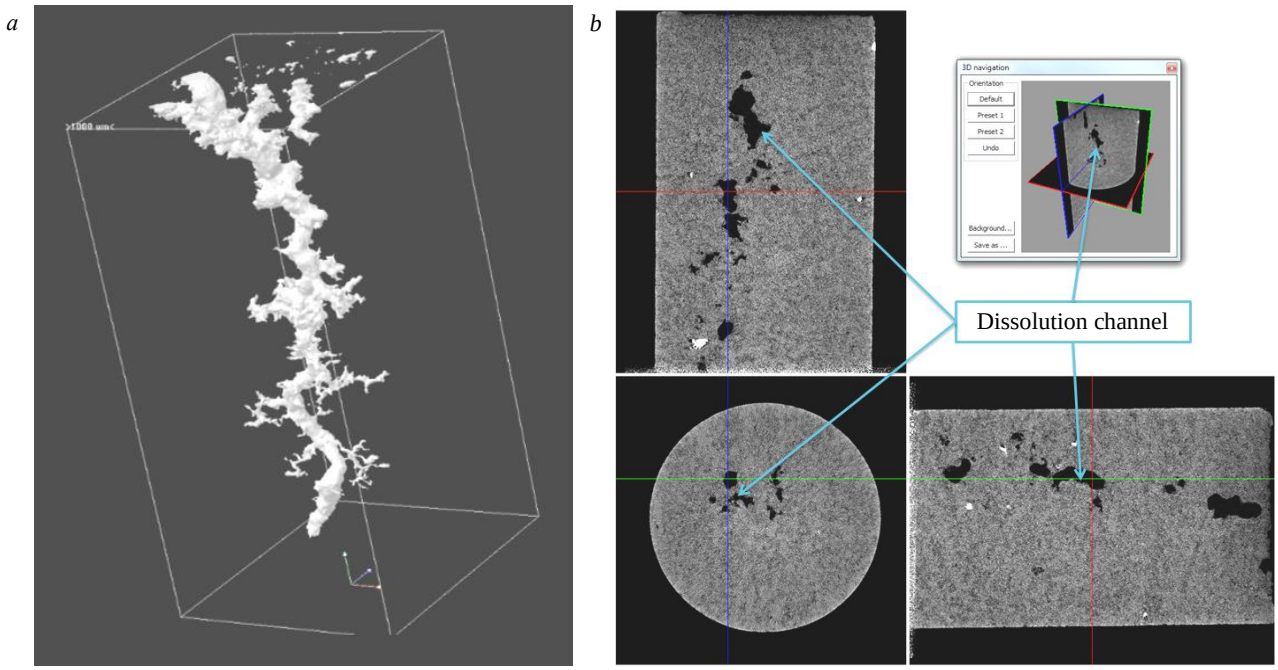


Fig.4. Internal volume of dissolution channels: *a* – 3D system and its view on X-ray tomographic slices; *b* – 2D system

to the initial sample: the number of pores increased by 3.7 times (from 761 to 2828); the maximum void size grew by 4.4 times (from 129 to 567 μm); and porosity increased by 11.2 times (from 0.04 to 0.45 %).

Next, zone III is observed, characterized by the development of a single extended dissolution channel (98.8 mm). The channel has a winding conical shape, measuring 1.9 × 2.8 mm at the entrance and 1.3 × 1.4 mm at the exit, with separate sections featuring the development of smaller and shorter lateral channels (Fig.4). The channel tortuosity T_c is 4.3 u.f.; the surface area S_c is 2.62 mm^2/mm^3, and

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the volume V_c is 0.37 cm^3. Overall, a significant structural change in the pore space of the sample is observed: pore and cavern sizes increased to 3.4 mm, with the median diameter nearly doubling. Porosity changed slightly to 11.5 %, the pore density parameter increased by 1.4 times, and the sample's permeability increased significantly – by four orders of magnitude.

For the second sample, characterized by a fracture-type reservoir, CT scanning revealed the presence of zones I and II (Fig.5), similar to the first sample but of smaller size. Additionally, a dissolution channel development zone (zone III) was observed, extending along the fractures. Unlike the pore-cavern type sample, the fracture-type sample exhibited two dissolution channels at the inlet face (see Fig.3, *h*), which merged into a single channel over a short distance (Fig.6, *a*). CT scanning showed that in this sample, the channel extended solely along the fracture and had a feather-like shape, with a more rounded entrance measuring 1.3 × 1.9 mm and an exit size of 0.8 × 2.5 mm (Fig.6). T_c is 3 u.f.; S_c is 7.9 mm^2/mm^3, and V_c is 0.092 cm^3.

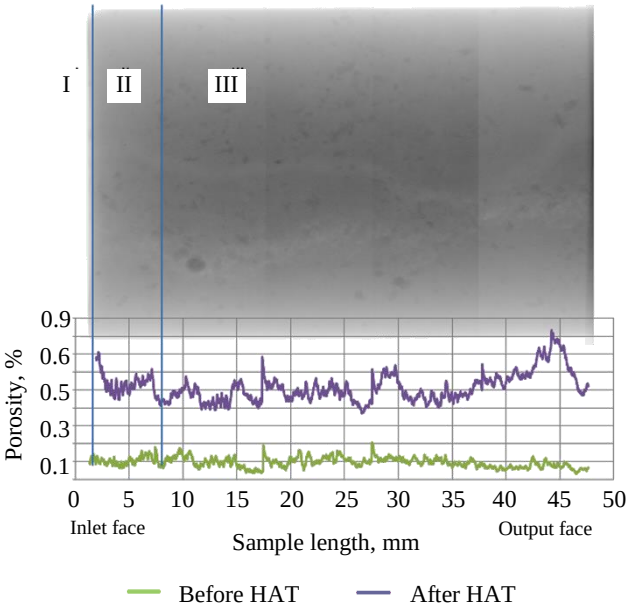


Fig.5. Graph of porosity distribution along the length of petrophysical sample T-02 before and after acid treatment

A significant structural change in the pore space is observed: the sizes of pores and caverns increased to 2.15 mm, with the median diameter increasing nearly fourfold. Porosity increased by 2.2 %, the pore density parameter tripled, and the sample's permeability significantly increased – by four orders of magnitude. The obtained morphological and petrophysical characteristics of the acid-affected zones in the samples, before and after HAT, are presented in the Table.

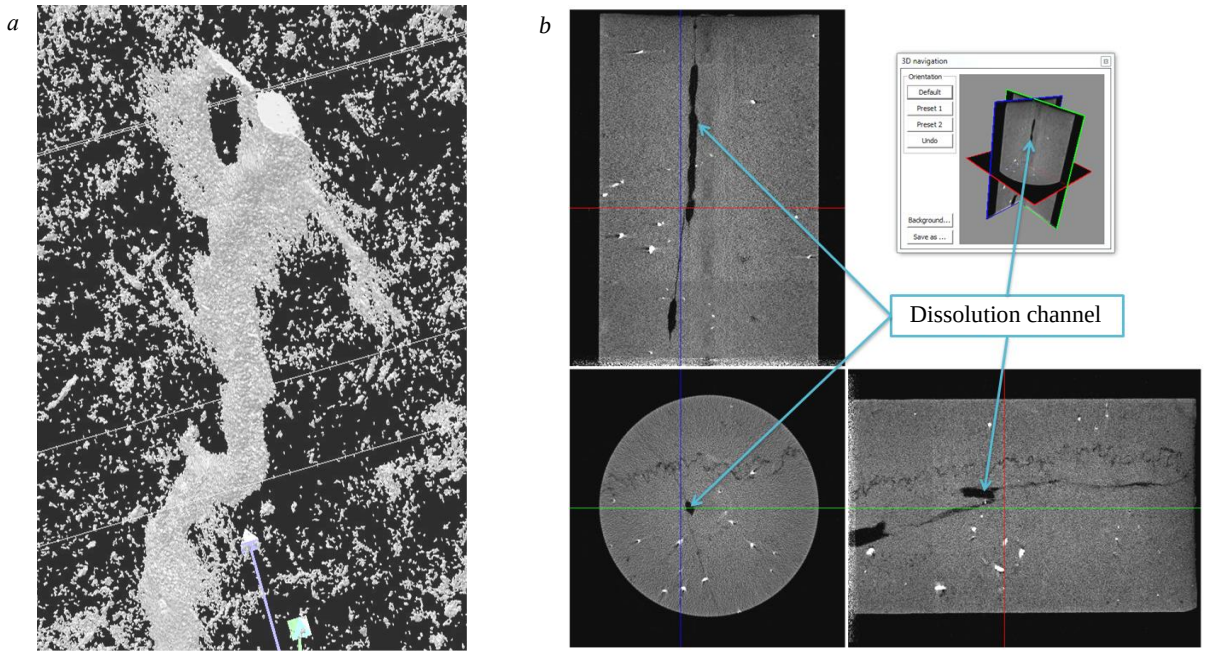


Fig.6. Internal volume of dissolution channels: *a* – 3D system and its view on X-ray tomographic slices; *b* – 2D system

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Summary of petrophysical properties of acid solution impact zones on pore-cavern (sample KP-01) and fracture (sample T-02) reservoirs

Parameter	KP-01						T-02					
	Zone I		Zone II		Zone III		Zone I		Zone II		Zone III	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
h, mm	–	0.53	–	7.4	–	38.6	–	0.34	–	4.4	–	41
V_p, cm^3	–	0.28	–	0.29	–	0.44	–	0.09	–	0.013	–	0.12
N_p, number	–		10593	17231	15891	21975	–		791	2828	670	2203
K_p, %	–		1	6.53	1.3	2.9	–		0.04	0.45	0.04	0.45
Md_p, μm	–		21.9	25	21.2	22.8	–		21.2	19.4	17.7	18.2
Pd_p, units/mm^3	–		233	379	349	483	–		18	65	16	51
S_p, mm^2/mm^3	–		62.4	225.5	87	162.7	–		2.9	17.4	2.6	14.4
			Dissolution channel						Dissolution channel			
N_c, number	–		1				–		2			
d_c, mm	–		1.9 × 2.8÷1.3 × 1.4				–		–			
l, mm	–		99				–		83			
T_c, u.f.	–		4.3				–		3			
V, mm^3	–		368				–		92.3			
S_c, mm^2/mm^3	–		262.1				–		794.3			
$v_{c.d}$, mm/min	–		1.5				–		4.9			

Notes: h – thickness of the HAT impact zone; V_p and V – dissolution and object volumes; N_c – number of dissolution channels; d_c – diameter of dissolution channels at the inlet and outlet faces; l – length of continuous dissolution channels; $v_{c.d}$ – dissolution channel dissolution rate.

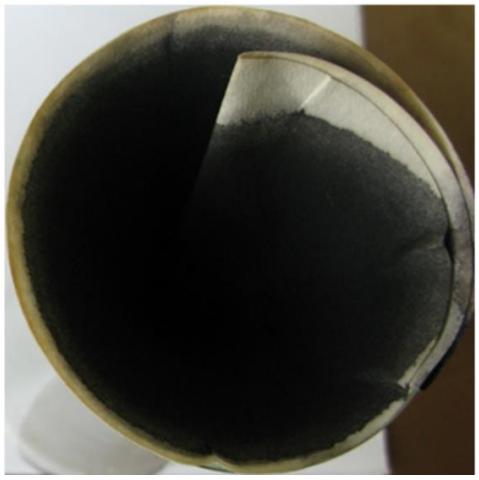


Fig.7. External appearance of asphaltene-resin-paraffin deposits on the filter

Thus, the pore transformation rates and dissolution channel development in the pore-cavern type reservoir are 1.5 mm/min, while in the fracture type reservoir they are 4.9 mm/min. The dissolution channel tortuosity in the first sample is 4.3 u.f., while in the second sample it is 3 u.f. The permeability of the rock changes from 0.8 to 5900 mD for the first type and from 0.2 to 5930 mD for the second type.

In addition to the dissolution of carbonate material and the formation of channels, the release of heavy hydrocarbons is observed in the samples. Fig.7 shows a photograph of the insoluble component (asphaltene, resin, and paraffin compounds, ARPC) on a paper filter. The movement of ARPC within the pore space can lead to their "smearing" along the walls of newly formed voids, potentially degrading the hydrodynamic connection between the dissolution channels and voids in the rock matrix – resulting in the process of clogging.

Conclusion

The results of filtration and digital X-ray tomography studies of core samples aimed at investigating the formation process of a high-conductivity channel (wormhole) in rock samples with a complex pore space structure are presented. The X-ray computed tomography method enabled a detailed examination of the rocks in both two-dimensional and three-dimensional spaces. It provided a comprehensive characterization of the pore space at the micro-level before and after acid treatment:

1. Under the specified acid solution injection regimes, highly permeable channels are formed, indicating that the injection regime was properly selected.

2. As a result of the study, the behavior of an acid solution commonly used in HAT in specific complex reservoirs of the oil rim of Orenburg oil and gas condensate field was identified. During the process, three zones of physicochemical impact were formed within the rock:

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• zone of constant contact between carbonate minerals and the acid solution;

• zone of structural transformation of the pore space of reservoirs, with the formation of caverns and short channels;

• zone of development of a continuous extended dissolution channel.

3. The geometry of dissolution channels formed in various complex reservoirs with different pore space types, namely fracture-type and pore-cavern type, was determined. Under the influence of hydrochloric acid, the fracture-type reservoir sample developed a conical channel with low branching, while the pore-cavern type reservoir sample formed a branched channel. Several practical conclusions can be drawn for the fracture-type reservoir:

• repeated acid treatment: since reservoirs undergo multiple acid treatments, the experiment showed that during subsequent treatments, the acid would follow the same dissolution channel without forming additional branches. To enhance channel branching at the micro-level, the use of diversion technologies is recommended to redirect the acid into the low-permeability rock matrix in wells subjected to repeated HAT;

• handling large fractures: in cases where the well intersects large extended fractures, the wormhole will also propagate along them. To ensure adequate stimulation of all zones near the wellbore, particularly the reservoir matrix, it is necessary to seal extended fractures before injecting acid into the formation. This can be achieved using plugging materials or suspensions.

4. In carbonate formations, the two studied types of complex reservoirs typically coexist. Since the rate of development of high-conductivity channels differs, it is recommended to use a chemical reagent that reduces filtration during acid treatment to equalize the acid treatment front. Additionally, dispersed systems such as emulsions and thickened solutions can be used.

5. Hydrocarbon compounds ARPC released during acid treatment can isolate dissolution channels from the voids in the rock matrix. This highlights the necessity of using a chemical reagent in the acid solution that dissolves ARPC or combining the chemical acid treatment method with thermal treatment methods. Based on the results of this study, thermo-acid treatment was conducted in several wells in the field, and on average, its effectiveness was higher (a 70 % increase in flow rate) compared to conventional acid treatment (a 40 % increase in flow rate).

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