



## Influence of Geological and Technological Parameters on Effectiveness of Hydrochloric Acid Treatment of Carbonate Reservoirs

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### ABSTRACT

Hydrochloric acid treatment is the most common oil production stimulation treatment to date. Yet, most of operations fail to deliver the targeted results. For a more competent design of acid treatment of carbonate reservoirs, flow studies on core samples are conducted preliminary to determine the most effective acid composition and the technology of its injection into formation. The authors believe that, at present, processing of flow research results is incorrect, as not all parameters are taken into account when making recommendations. This study examined the influence of geological and technological parameters on effectiveness of hydrochloric acid treatment. In the course of studies using the flow unit and X-ray tomography, a number of factors have been identified that affect the outcome of the treatment. The volume of acid composition required to create a highly conductive channel in a core sample is a parameter using which it is possible to conduct a comparative analysis of effectiveness of the acid compositions under test and the methods of their injection. Therefore, exactly this parameter is used as a core in this paper, based on which the authors have derived an integrated indicator that provides for the most reliable evaluation of the flow study results. Using this indicator, it is possible to provide more competent recommendations as to the choice of acid compositions and the technology of oilfield hydrochloric acid treatments, which will provide the greatest effect of the planned operations to enhance oil recovery.

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### NOMENCLATURE

$V_{AC}$	Acid composition volume in pore volume, required to create a through channel	$k_p$	Coefficient of absolute gas permeability of a core sample before treatment ( $10^{-3} \mu m^2$ )
$q$	Rate of acid composition injection into a core sample ( $cm^3/min$ )	$P_{inj}$	Maximum excess pressure of acid composition injection into a core sample (MPa)
Karbon	Carbonate content of a rock sample (%)		

### 1. INTRODUCTION

More than 50% of oil in the Volga-Ural region (Russia) is recovered from carbonate rocks that feature complex geology, low porosity and permeability properties. This causes a wide range of issues in their development [1]. Various geotechnical procedures (GTP) applied to

enhance reservoir properties, increase reservoir-to-well hydrodynamic connectivity and decrease flow resistance in the bottom hole zone (BHZ).

Hydrochloric acid treatment (HAT) is one of the most common methods of oil production stimulation for carbonate rocks, as of today [2–6]. The high effectiveness of acid treatment results from the growth of field

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indicators following the geotechnical procedures. The relevance of scientific studies in the interaction of hydrochloric acid compositions with carbonate rocks is stipulated by a very extensive practice of application of this technology.

To enhance the effectiveness of the hydrochloric acid effect on reservoir, a large number of modifications of acid compositions (AC) are being currently developed, contributing to the individual nature of the process of the treatment of productive sediments near wellbore [7–9]. To exercise a competent approach to the design of hydrochloric acid treatment, physical and chemical properties of formation fluids, lithologic and mineralogical composition, type of rock paleolithic facies and pressure-temperature conditions will be taken into account [10]. Furthermore, the success of well stimulation measures is achieved by preliminary evaluation of oil production growth, carried out with the help of hydrodynamic simulators [11, 12] and using the results of laboratory studies [13–21].

Simulation of the AC injection into oil-bearing reservoir is performed under laboratory conditions with the help of core testing flow units. Up-to-date laboratory equipment enables to recreate realistic reservoir conditions when performing a HAT. The key objective of the flow unit application is to determine the effectiveness of a particular AC under set conditions of its injection into a rock. One of the principal evaluation parameters is the volume of acid composition in the pore volume required for ‘breakthrough’, i.e. the creation of a high-conductive channel. This parameter allows performing an integrated analysis of AC selection effectiveness and technological parameters of its injection.

As part of this research, works presenting core sample flow studies and evaluation of their results as per above indicator have been reviewed. The authors believe that currently the processing of flow test results is incorrect, due to the determination of AC efficiency based on a single parameter indicated in recommendations when conducting the hydrochloric acid treatment at the oilfield.

Thus, for example, works [22–24] present diagrams of the obtained dependency of the AC amount in pore volume at breakthrough on the rate of its injection into a rock sample. The above papers demonstrate a relationship between these parameters. The presented dependency is used to study and derive results of the AC application effectiveness determination based on the results of laboratory tests. The analysed materials have become the reason for doubts, which called for the assumption of the presence of a number of other additional parameters that comprehensively affect the acidizing effectiveness, enable reliable evaluation of the results of core sample flow studies and provision of recommendations on hydrochloric acid treatment to maximize well productivity. This study is relevant due to the small number of successful treatments at real sites,

despite preliminary laboratory studies, extensive experience in the application and simplicity of this bottomhole zone treatment technology [25, 26].

## 2. MATERIALS AND METHODS

### 2. 1. Effectiveness Factors in Acid Treatment

To support the advanced hypothesis, the objective of the integrated research of factors that affect the effectiveness of acidification will allow to competently design hydrochloric acid treatment of wells to achieve the target values. To achieve this objective, authors carried out flow tests on standard core samples using AFS-300 modular computer-controlled system. The rock samples were collected from a carbonate reservoir of a field that is a part of the petroleum play of Perm Krai. Due to high heterogenic nature and stratification, the core samples were collected for research over the entire interval of oil-saturated formation thickness from the wells of the target facility

Mineralogical composition, as it is known, impacts the success of the HAT. To reduce errors in remove the further study, experiments were carried out to determine the carbonate content of samples from the formation under study. These samples were referenced by depth against the core samples tested on AFS-300 flow unit, which was implemented to minimize errors. The experiments were performed using a KM-04M carbonate metering device that allows determining the mass ratio of calcite, dolomite, and insoluble residue in the sample under study. According to obtained results, quite a wide range of variation in the carbonate content of the deposit understudy was established - from 82.6 to 97.9 %

In the next stage, the principal part of laboratory work was conducted on the above mentioned flow unit. For more extensive coverage of the results and to accurately establish the factors that affect the amount of AC when forming a ‘wormhole’, tests were conducted on 27 samples from the target facility. The acid composition was selected based on the analytical review of scientific works, FLUXOCORE-210 has been selected as the most effective acid composition that delivered proven application results [27]. According to obtained field data, it is assumed that the following factors influence the determination of the AC volume in the pore volume at breakthrough  $V_{AC}$ :

- Karbon – carbonate content of a rock sample (%);
- $q$  – rate of acid composition injection into a core sample ( $\text{cm}^3/\text{min}$ );
- $P_{inj}$  – maximum excess pressure of acid composition injection into a core sample (MPa);
- $k_p$  – coefficient of absolute gas permeability of a core sample before treatment ( $10^{-3} \mu\text{m}^2$ ).

Prior to AC injection into the core sample, the  $k_p$  value was determined using the flow unit for further

dependency study. It was determined in advance by the authors, the injection rate was constant during the process of AC injection due to stable operation of the injection pump. Using pressure sensors on two ends of the standard core sample, the flow unit was recording the values from the two ends continuously during the experiment. After the test, when processing the results, the authors determined  $P_{inj}$  from the graphs and deduced the dependencies presented hereinafter.

The authors have proposed an integrated indicator given in Equation (1). This study is mainly aimed to investigate the influence of the integrated indicator on the  $V_{AC}$  parameter.

$$k = \frac{P_{inj} \cdot q}{\frac{K_{arbo}}{100} \cdot k_p} \quad (1)$$

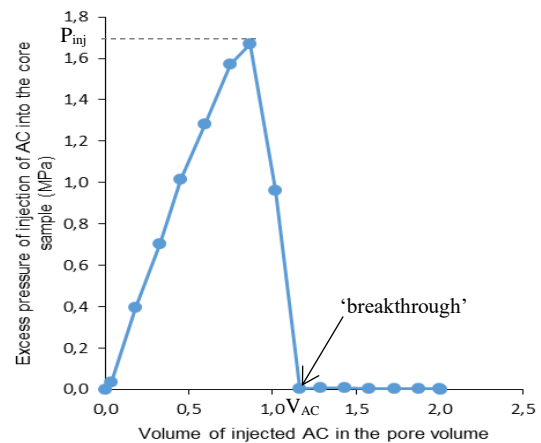
The arrangement of parameters in the numerator and denominator relies on the  $V_{AC}$  increase/decrease through the increase/decrease of independent parameters. For example, it is known that a sample with high permeability from straight calcite requires a smaller amount of acid to create a high-conductive channel. Then the  $V_{AC}$  will be increasing with higher pressures and injection rates.

## 2. 2. Conducting of Flow and Tomography Studies

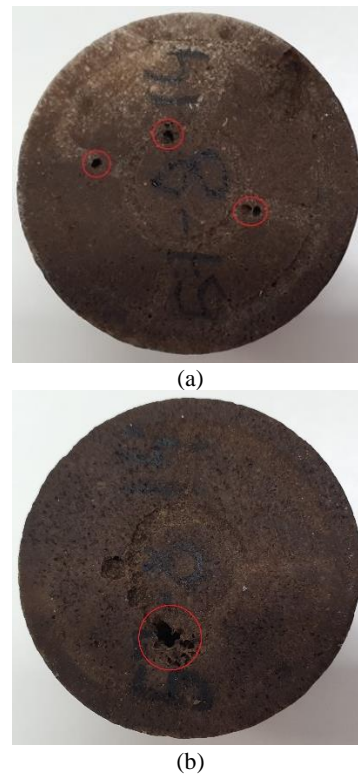
To check the advanced assumption given in Equation (1), the procedure of determination of correlation dependency between the presented parameters was carried out, by analogy with the work reported in literature [28].

For example, the authors hereof have presented processing of the results that describes the process of  $V_{AC}$  determination upon completion of testing of a rock samples under test in the flow unit. A simulation of acid treatment design at reservoir pressure of 13.2 MPa,  $P_{inj}$  was 1.668 MPa, where the 'wormholing' has commenced. The analysis of the diagram in Figure 1 allowed to determine that the injected volume of acid, which was equal to 1.162 in pore volume, created a valid through the channel, the beginning and the end of which can be seen at the ends of the core sample (Figure 2). To make the creation of a full end-to-end channel more convincing the authors carried out studies on the microfocus system of X-ray test with the function of computer tomography on the basis of X-ray of Nikon X-ray unit Metrology XT H22. This system allows visualizing the void space by creating a 3D model. The results of the study conducted before and after the AC injection into the rock sample allow to visually assess changes in the structure of the void space. Based on these results, it is possible to accurately determine the degree of void space growth, as well as the direction and nature of 'wormholing' in the rock sample when simulating the AC injection in the flow unit.

Figure 3 shows images of 3D models of the void space of the sample under study before and after AC injection in the flow unit. Comparative analysis of the

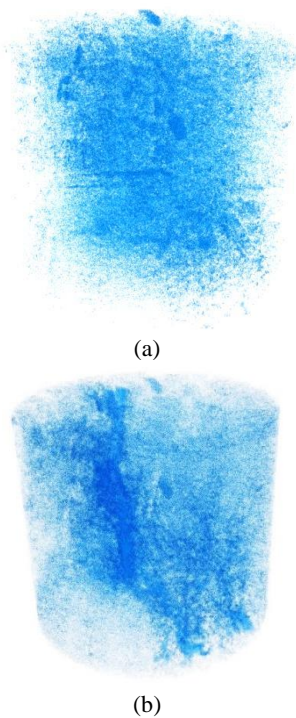


**Figure 1.** Dynamics of change in excess pressure of AC injection into the core sample with volume of injected AC in pore volume



**Figure 2.** Photographs of core end faces after acid treatment: (a) inlet; (b) outlet

image of 3D-models of the void space structure allows to draw a conclusion about the growth of the total void and creation of a high-conductive channel in the sample under study from the reviewed productive formation. The figure above clearly shows the system of voids in the sample before AC treatment, which changes significantly after the flow test. Figure 3(b) visually illustrates the formed 'wormholing' that commenced at  $P_{inj}$  equal to



**Figure 3.** Images of 3D models of void space structure of the sample under study: a) before acid treatment; b) after acid treatment

1.668 MPa. During the injection of  $V_{AC}$  equal to 1.162, a valid through channel was formed under the influence of excessive injection pressure and AC solvent power.

The authors hereof tested all 27 samples following the same pattern to establish the characteristics of dependencies and confirm the proposed hypothesis. The significance of the proposed expression constitutes the larger proportion, because with its help, the evaluation of the choice of parameters at hydrochloric acid treatment will comprehensively cover a range of factors rather than a single one.

### 3. RESULTS OF CORRELATION DEPENDENCIES DETERMINATION

Upon the detailed description of the laboratory method of determining the  $V_{AC}$  value, and the 'wormhole' representation we can proceed to determination of characteristics of the strength of the relationship between independent parameters and  $V_{AC}$ . Expertise in the correlation analysis allows to estimate the significance of linear relationship between two sets of values. With the help of linear coefficient of pair correlation, it is possible to give a statistical estimation of the calculations made by the authors, i.e. to check the considered dependencies for adequacy. Figure 4 show diagrams of  $V_{AC}$  dependencies on  $P_{inj}$ ,  $q$ , Karbon and  $k_p$ , respectively, based on the

results of laboratory testing of 27 core samples. The pair correlation coefficients presented in Table 1 were derived from these graphs, as well.

By analysing the diagrams (Figure 4) and the values in Table 1, we can qualitatively characterize the strength of relationship of parameters on the Chaddock scale. The coefficient of pair correlation between the number sets of  $q$  and  $V_{AC}$  is very low, so there is no relationship between these parameters. This suggests the wrong approach to evaluating the results given in the above works. The presented results of the laboratory studies show that it is impossible to derive any dependencies on the two parameters under consideration, therefore, 'validated' conclusions on these indicators are incorrect. It is also noted that the relationship between the two pairs of sets  $P_{inj} - V_{AC}$  and  $k_p - V_{AC}$  are characterized by high strength. High negative value of the pair correlation coefficient corresponds to the second pair of number sets, which indicates the inverse relationship of the specified parameters, as assumed in Equation (1). Given that the pair correlation coefficients of  $q - V_{AC}$  and Karbon -  $V_{AC}$  sets are very small, it is impossible to confirm the position in the numerator or denominator for each independent parameter.

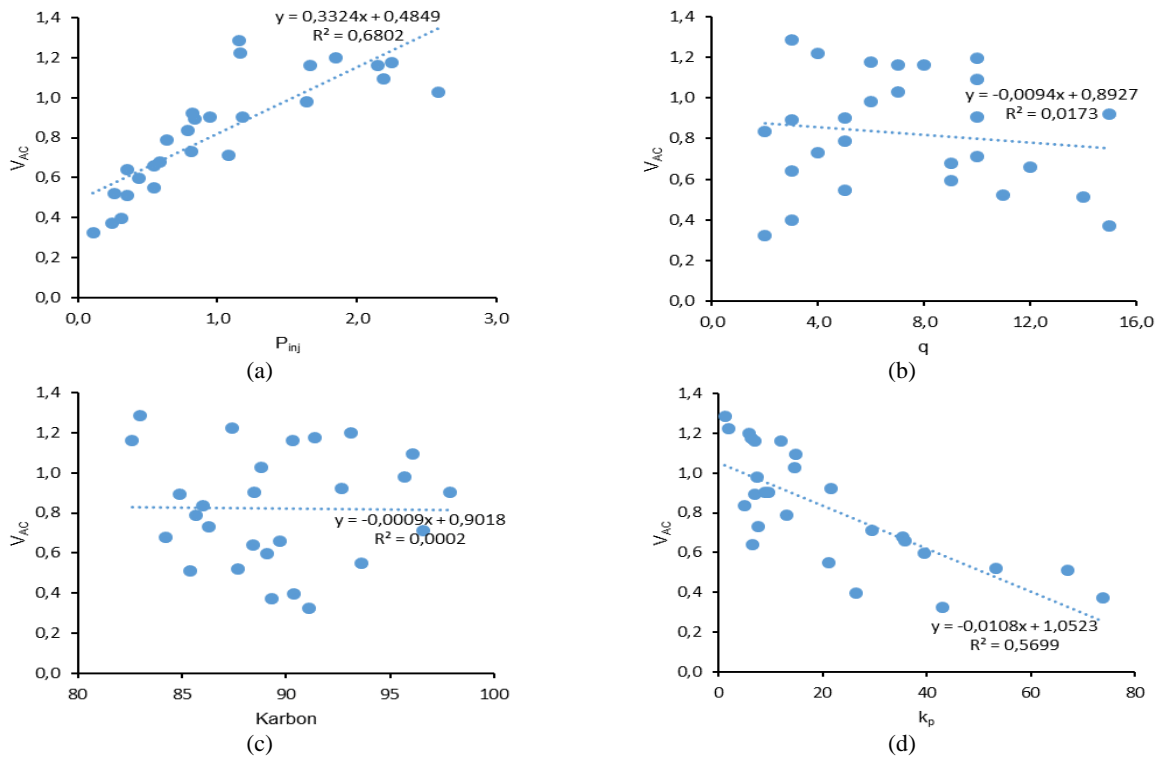
The results of the conducted analysis of dependencies of independent parameters and  $V_{AC}$  allow to state that the research of one parameter only makes it unsubstantiated to process flow studies with the subsequent provision of recommendations on HAT at problem facilities due to underestimation of other factors. In the absence of analysis of other parameters, oil production stimulation jobs may fail to achieve the targeted results.

Further, the relationship between the integrated indicator proposed by the authors hereof and the  $V_{AC}$  has been studied, the diagram of their dependency given in Figure 5. The linear coefficient of the pair correlation is 0.874, which is significant. On the Chaddock scale, the coefficient characterizes a very strong relationship. It means that the proposed idea of the integrated approach to the evaluation of the AC effectiveness and injection conditions, based on the  $V_{AC}$  parameter, has a statistical validity, since there is a high correlation relationship.

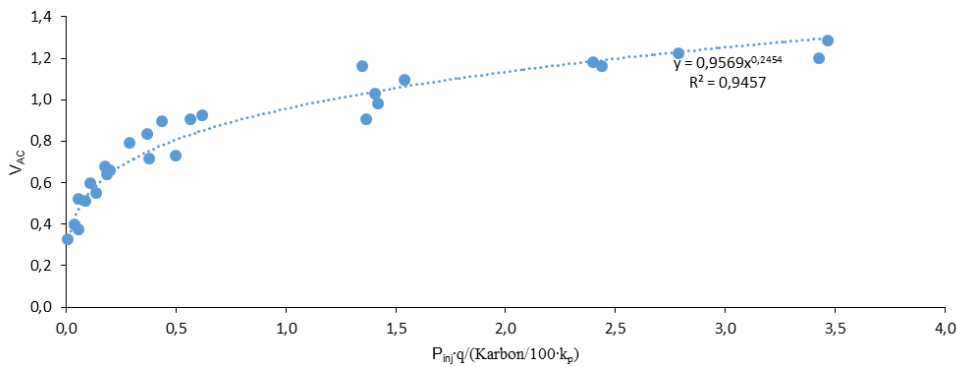
Visually, Figure 5 shows that the dependency trend (Equation (1)) tends to the power law. This is also confirmed by the highest value of approximation

**TABLE 1.** Obtained Coefficients of Pair Correlation of Parameters Influencing the AC Volume in the Pore Volume at Breakthrough

Parameter	Pair Correlation Coefficient
$P_{inj}$	0.82472
$q$	-0.13149
Karbon	-0.01289
$k_p$	-0.75491



**Figure 4.** Diagrams of dependency of AC volume in pore volume at breakthrough on: a) maximum excess pressure of AC injection into core sample; b) AC injection rate into core sample; c) carbonate content of rock sample; d) absolute gas permeability coefficient of core sample before treatment



**Figure 5.** Diagram of dependency of AC volume in pore volume at breakthrough on the integrated indicator proposed by the authors herein

coefficient  $R^2$  (Table 2). The reviewed dependency is best described by the power-law equation given below (Equation (2)):

$$V_{AC} = 0,9569 \cdot \left( \frac{P_{inj} \cdot q}{\frac{Karbon}{100} \cdot k_p} \right)^{0,2454} \quad (2)$$

This conclusion is based both on visual impressions and on rigorous quantitative calculation using approximation coefficient. Due to the high value of valid approximation between such two sets of numbers as an integrated

**TABLE 2.** Obtained Values of Approximation Coefficients for Various Regression Equations

Dependency	R-Squared Value
Exponential	0.6271
Polynomial	0.8791
Linear	0.7636
Power-Law	0.9457
Logarithmic	0.9176

indicator and  $V_{AC}$ , we can say that the proposed indicator has a valid proof of application in the comparative characteristics of the AC effectiveness and the technological conditions of its injection. The average inaccuracy of the calculated  $V_{AC}$  value is 7.1%. It is critical to use this parameter for more substantiated recommendations on acid treatment of carbonate reservoirs based on the results of flow and X-ray tomography studies. To make the most of the oil recovery enhancement, the integrated indicator including lithologic, mineralogical and flow properties of the reservoir, as well as technological parameters of AC injection, shall be taken into account. At present, the given dependency is unique and relevant, since a large number of hydrochloric acid treatment jobs do not deliver target figures, due to under-researched features of the acidification process

#### 4. CONCLUSION

In the conclusion, it is noted that the dependency (1) advanced by the authors has been confirmed. This dependency is validated by statistical indicators calculated based on laboratory research on the core samples from the oilfield in Perm Krai. The authors emphasize the fact that the  $V_{AC}$  is affected by a number of factors. These parameters depend on the way acid is injected into the core sample, and flow, lithologic and mineralogical properties of the rock sample. An individual study of each independent parameter may cause invalid results. Following the study results, the integrated indicator has been proposed, which can be used as a reference coefficient to evaluate the AC effectiveness and to determine the most optimal injection technology. Further practical application of this set of parameters will result in an increased number of efficient geotechnical procedures and enhance the effectiveness of oil production stimulation methods.

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## Persian Abstract

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### چکیده

تیمار چاه نفت با اسید هیدروکلریک رایج‌ترین روش تحریک تولید نفت تا به امروز است. با این حال، بسیاری از عملیات نتوانسته نتایج هدفمندی را ارائه دهد. به منظور طراحی صحیح‌تر برای تصفیه اسید مخازن کربنات، مطالعات جریان در نمونه‌های هسته اولیه برای تعیین مؤثرترین ترکیب اسید و فناوری تزریق آن در شکل‌گیری انجام می‌گیرد. نویسندگان معتقدند، در حال حاضر، پردازش نتایج تحقیقات جریان نادرست است، زیرا همه پارامترها هنگام تهیه در نظر گرفته نمی‌شوند. در این مطالعه تأثیر پارامترهای زمین‌شناسی و فناوری در اثربخشی تیمار اسید هیدروکلریک مورد بررسی قرار گرفت. در طی مطالعات با استفاده از واحد جریان و توموگرافی اشعه ایکس عوامل مختلفی شناسایی شده‌اند که بر نتیجه درمان تأثیر می‌گذارد. حجم ترکیب اسید مورد نیاز برای ایجاد یک کانال بسیار رسانا در یک نمونه اصلی یک پارامتر است که با استفاده از آن می‌توان تجزیه و تحلیل مقایسه‌ای از اثربخشی ترکیبات اسیدی مورد آزمایش و روش‌های تزریق آن‌ها را انجام داد. بنابراین، دقیقاً از این پارامتر به عنوان هسته در این مقاله استفاده می‌شود، بر اساس آن نویسندگان یک شاخص یکپارچه را تهیه کرده‌اند که قابل اطمینان‌ترین ارزیابی نتایج مطالعه جریان را فراهم می‌کند. با استفاده از این شاخص، می‌توان توصیه‌های صحیح‌تری در مورد انتخاب ترکیبات اسیدی و فناوری تیمارهای اسید هیدروکلریک اسید نفتی ارائه داد، که بیشترین تأثیر عملیات برنامه‌ریزی شده را برای تقویت بازیافت نفت ارائه می‌دهد.

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