ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

№5
2025

ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

5 (473)

SEPTEMBER – OCTOBER 2025

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2025

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: «Central Asian Academic Research Center» LLP (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ39VPY00025420,** issued 29.07.2020.
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *Геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*
Мерзімділігі: жылына 6 рет.
http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Собственник: ТОО «Центрально-азиатский академический научный центр» (г. Алматы).
Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.
Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*
Периодичность: 6 раз в год.
http://www.geolog-technical.kz/index.php/en/

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 5. Number 473 (2025), 227–239

https://doi.org/10.32014/2025.2518-170X.560

IRSTI 52.47.27
UDC 622.276.6:553.98:550.8

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INFLUENCE OF VARIATION COEFFICIENT OF NON-HOMOGENEITY ON THE EFFICIENCY OF SELECTION OF OPTIMAL TECHNOLOGY OF HYDROCHLORIC ACID TREATMENT

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Abstract. The work's pertinence lies in its contribution to the enhancement of scientific and methodological approaches in the design of measures to treat bottomhole formation zone using elements of computer modelling. At the current stage of development and operation of oil fields, subsoil users often face problems caused by the lack of full consideration of emergent systems in the construction of various models of forecasting geological and technological indicators and low level of field data preparation. Consequently, the obtained dependencies frequently

lack physical significance, impeding reliable interpretation and integration into the production process. This issue is also relevant for carbonate reservoirs of the Bashkir-Serpukhov deposits of the Solikamsk depression, located in the oil-bearing areas of the Perm Territory of the Russian Federation. These reservoirs are distinguished by non-linear variations in the geological and physical characteristics of reservoir rocks. This necessitates the identification of regularities across diverse model parameters, as well as the utilisation of artificial intelligence, pattern recognition, and similarity methods for the purpose of replicating practical technical and technological solutions, thereby enhancing well productivity. The employment of sophisticated modelling techniques, particularly the incorporation of the porosity heterogeneity index, has led to the identification of methodologies for enhancing the design of hydrochloric-acid treatments. Furthermore, recommendations have been provided for the selection of candidate wells, both for the wells themselves and for the selection of wells.

Keywords: heterogeneity in porosity, design of hydrochloric acid treatment, carbonate reservoirs of the Bashkir-Serpukhov deposits, peculiarities of geological structure, well productivity improvement

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АЙНЫМАЛЫ БІРТЕКТІЛІК КОЭФФИЦИЕНТІНІҢ ТҰЗ ҚЫШҚЫЛЫН ӨҢДЕУДІҢ ОҢТАЙЛЫ ТЕХНОЛОГИЯСЫН ТАҢДАУ ТИІМДІЛІГІНЕ ӘСЕРІ

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Аннотация. Жұмыстың өзектілігі қабаттың түп аймағын өңдеу шараларын жобалау бойынша ғылыми-әдістемелік тәсілдерді жетілдіру қажеттілігімен байланысты, бұл үшін компьютерлік модельдеу элементтерін пайдалану маңызды. Қазіргі уақытта мұнай кен орындарын игеру және пайдалану кезеңінде жер қойнауын пайдаланушылар көбінесе геологиялық-технологиялық көрсеткіштерді болжау модельдерін құру кезінде жүйелердің эмерджентілігін толық есепке алмау және өндірістік деректердің жеткіліксіздігі сияқты мәселелерге тап болады. Көбінесе алынған тәуелділіктер физикалық мағынадан айырылған, бұл олардың сенімді интерпретациясын және өндірістік процеске енгізілуін қиындатады. Бұл мәселе Ресей Федерациясының Пермь өлкесіндегі мұнайлы аймақтарда орналасқан Соликамск депрессиясының башқұрт-серпухов шөгінділеріндегі карбонатты коллекторлардың мұнай кен орындары үшін де өзекті. Олар коллектор жыныстарының геологиялық-физикалық қасиеттерінің сызықты емес өзгеруімен ерекшеленеді, бұл модельдердің әртүрлі параметрлері арасындағы заңдылықтарды анықтауда және ұңғымалардың өнімділігін арттыру саласында өзекті техникалық-технологиялық шешімдерді тарату үшін жасанды интеллект әдістерін, үлгілерді тану және ұқсастық тәсілдерін қолдануда қиындықтар тудырады. Кешенді модельдеуді қолдану арқылы, атап айтқанда, кеуектілік бойынша біртектілік көрсеткішін енгізу арқылы тұз-қышқылды өңдеуді жобалауды жетілдіру жолдары анықталды және сәйкес шараларды жүргізу үшін де, сондай-ақ керн үлгілеріне қосымша зерттеулер жүргізу үшін де ұңғымаларды таңдау бойынша ұсыныстар берілді. Бұл зерттеулер объектілердің геологиялық құрылымының ерекшеліктерін анықтауға және сүзгіштік-коллекторлық қасиеттердің өзгеру заңдылықтарын анықтауға бағытталған. Есептелген техникалық-экономикалық көрсеткіштер ұсынылған тәсілдің өзектілігін дәлелдейді және оны қалдық мұнай қорларын игеру кезінде толық немесе шектеулі ақпарат жағдайында қолдану мүмкіндігін негіздейді.

Түйін сөздер: кеуектілік бойынша біртектіліксіздік, тұз-қышқылды әсер етуді жобалау, башқұрт-серпухов шөгінділерінің карбонатты коллекторларының кен орындары, геологиялық құрылымның ерекшеліктері, ұңғымалардың өнімділігін арттыру

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ВЛИЯНИЕ ВАРИАТИВНОГО КОЭФФИЦИЕНТА НЕОДНОРОДНОСТИ НА ЭФФЕКТИВНОСТЬ ПОДБОРА ОПТИМАЛЬНОЙ ТЕХНОЛОГИИ СОЛЯНО-КИСЛОТНОГО ВОЗДЕЙСТВИЯ

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Аннотация. Актуальность исследования обусловлена необходимостью совершенствования научно-методических подходов к проектированию мероприятий по обработке призабойной зоны пласта с применением элементов компьютерного моделирования. На современном этапе разработки нефтяных месторождений недропользователи часто сталкиваются с трудностями, связанными с неполным учетом эмерджентных свойств систем при моделировании геолого-технологических показателей и низким качеством промысловых данных. Полученные зависимости нередко оказываются физически неинтерпретируемыми, что затрудняет достоверную интерпретацию и внедрение результатов в производственный процесс. Данная проблема характерна и для залежей карбонатных коллекторов башкирско-серпуховских отложений Соликамской депрессии (Пермский край, Россия), которые отличаются нелинейным изменением геолого-физических свойств пород-коллекторов. Это требует применения методов искусственного

интеллекта, распознавания образов и аналогий для тиражирования оптимальных технико-технологических решений по повышению продуктивности скважин. Использование комплексного моделирования, в частности внедрение показателя неоднородности по пористости, позволило определить направления совершенствования проектирования солянокислотных обработок и сформировать рекомендации по выбору скважин-кандидатов для проведения данных мероприятий, а также по выполнению дополнительных исследований керновых образцов. Полученные технико-экономические показатели подтверждают актуальность предложенного подхода и обусловливают возможность его применения при разработке остаточных запасов нефти в условиях ограниченной информации.

Ключевые слова: неоднородность по пористости, проектирование солянокислотного воздействия, карбонатные коллекторы, башкирско-серпуховские отложения, геологическое строение, производительность скважин

Introduction. The intelligent support of oil field development is closely related to the use of multilevel mathematical models, the construction of which is carried out within the framework of analysis, interpretation and accounting of geological and field data. The active introduction of digital systems to support managerial decision-making has served as a basis for the creation of various approaches to solving the problems of reliable application of known algorithms in describing the dynamics of nonlinear oil production processes. In the context of the intensive depletion of conventional hydrocarbon resource bases, the priority for subsoil users is the development of complexly constructed low-productive deposits, the reserves of which are confined to hard-to-recover categories (Astafyev & Mitrofanov, 2024; Brekhuntsov, 2025; Kotenev, et al., 2024; Mahdavi et al., 2025; Saduakassov et al., 2024). A critical factor in the effective deployment of a specific data processing methodology is the ability to leverage the generated results to address a defined set of problems, regardless of the volume, density, and relevance of the initial data. However, this often presents a challenge due to the following reasons.(Hong et al., 2025; Kuleshova, 2024; Sui et al., 2025)

- the wide variability of geological and physical conditions across reservoirs;
- the low level of information updating and lack of unified criteria for evaluating the feasibility of incorporating laboratory study results into core modelling processes;
- the need to construct reference dependencies and utilize them to characterize parameter dynamics;
- the rise in heterogeneity when employing certain complex indicators;
- the inability to perform validation operations on the obtained dependencies for their relevance and timeliness.

Despite the high rate of implementation of advanced digital solutions in the practice of oil field development, their effectiveness is characterised by

ambiguity, which requires comprehensive development of the relevant scientific and methodological foundations, including through the identification of hidden regularities between various geological and field parameters (Duthie et al., 2025). The application of advanced techniques, such as artificial intelligence, pattern recognition, and data structuring methods for processing large volumes of information, is a topic of considerable interest among subsoil users. These approaches aim to comprehensively incorporate the best engineering practices. Furthermore, the existence of certain regularities between the parameters reflecting the geological and physical characteristics of productive formations and the fluids saturating them enables subsoil users to adopt a well-reasoned approach when developing methodologies for designing specific types of interventions.

Materials and basic methods. Accurately characterizing the nature of heterogeneity is crucial for effectively planning and preparing various activities (Wang et al., 2025; Ying et al., 2025; Zuobin et al., 2025). Despite the extensive experience in computer modeling of various oil field development processes, the existing approaches do not always enable their practical application in the complex mining and geological conditions of reservoir development. The author's algorithms were utilised to execute various states of modelling, employing a combination of established statistical and numerical approaches. The author's algorithms were based on the interpretation of previously constructed dependencies reflecting the influence of heterogeneity on the main filtration-capacitance properties of reservoir rocks, reservoir conditions and physical and chemical properties of the produced products. The employment of a multi-component approach in this study enabled the reduction of uncertainty and the minimisation of the probability of making low-efficiency decisions when implementing the results in the processes of design and support of hydrochloric-acid stimulation of the reservoir. To evaluate the potential of using Lorentz coefficients in addressing various field development challenges, let us examine one approach to their comprehensive interpretation, using the design of hydrochloric acid treatment as an example (Ramy et al., 2025; Kulesho, et al., 2024; Lugo et al., 2023; Qamruzzaman et al., 2023; Ramy et al., 2025). The study focuses on the carbonate reservoirs located in the Perm Krai region, specifically within the Bashkir-Serpukhov sediments of the Solikamsk depression. The geological structure of the study area is characterized by a high degree of heterogeneity in the void space, as confirmed by geophysical and petrophysical data. This heterogeneity poses some limitations on the application of statistical approaches to data interpretation. Additionally, within certain tectonic-stratigraphic units, a non-linear pattern of natural fracturing is observed, which affects the relevance of estimating actual well productivity. An analysis of reservoir development indicators over the past five years reveals the following: in the Bashkir-Serpukhov deposits, the efficiency of hydrochloric acid treatments in reservoirs with a well-developed pore structure is approximately 10-15% lower compared to treatments in reservoirs with natural micro- and macrofractures. Conversely, an increase in the number of pore channels has a positive influence on the recovery time of the wells.

When examining the heterogeneity in porosity identified through geophysical studies, we will analyze the results of treating the bottomhole formation zone using the classical HCl composition. By solving the system, we will determine the values of relevant indicators along the x and y-axes for the three most common scenarios encountered by oil field development operators: effective treatment yielding the predicted oil flow rate, ineffective treatment resulting in no or insignificant increase in oil flow rate that does not offset the economic costs, and a technological effect of well treatment lasting less than 50% of the normative period.

$$\begin{cases} y = \frac{\sum h_i \cdot m_i}{\overline{h_m}} \\ x = \frac{\sum h_i}{h} \end{cases}, \quad (1)$$

where m_i – is the porosity of the i -th layer, determined based on geophysical survey results;

h_m -is the average thickness of the layers, adjusted to the range of porosity variation;

h_i- is the thickness of the i -th layer.

The provided figure 1 illustrates the quantitative and qualitative changes in geological heterogeneity of porosity following the injection of hydrochloric acid composition. This analysis is based on data from three wells that traversed the Bashkir-Serpukhov deposits within the Solikamsk Depression.

The area representing the minimum heterogeneity index is bounded by the diagonal of square AB and the curve labeled 2, which corresponds to the results of ineffective hydrochloric acid injection and limited penetration depth into the formation. In this case, the agent distribution radius within the bottom-hole zone is constrained, with absolute values of 0.3 on the x-axis and 0.4 on the y-axis, possibly due to the incorrect implementation technology for the current geological and physical conditions of the pay zone. The maximum heterogeneity index in porosity, as determined by geophysical studies, is found within the area bounded by the diagonal of square AB and the curve labeled 3. Here, the acid composition's penetration depth into the formation is higher compared to the previous scenario, as confirmed by the absolute values of 0.4 on the x-axis and 0.74 on the y-axis, which characterize the radius of the injected agent's spread.

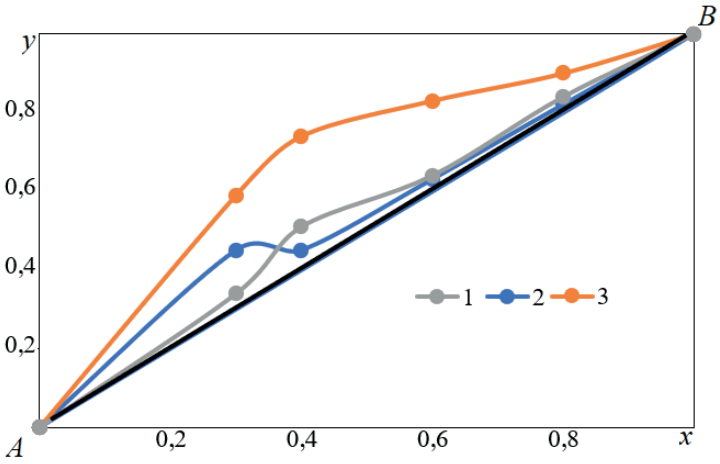

Figure 1 - Trend of variation of the geological heterogeneity index by porosity after bottomhole formation zone treatment

The curve labeled 1 is most similar in characteristics to curve 3, as reflected in the presence of almost 'mirror' changes in the y-axis values and their further smoothing parallel to line AB. However, the number of intervals with insignificant x-value changes is 95% greater for curve 1 compared to curve 3, on the basis of which the results of hydrochloric acid treatment differ in quantitative and qualitative characteristics.

Results. When comparing the results obtained from modeling carbonate reservoirs of the Bashkirian-Serpukhovian deposits within the Solikamsk Depression, a certain pattern influencing the effectiveness of near-wellbore zone treatment has been identified. Specifically, during the saturation of the porous medium with the injected agent, the penetration depth of the composition primarily depends on the thickness of the formation, whereas porosity plays a secondary role, merely determining the interconnectivity of filtration zones and the maximum possible volume under current geological and technological conditions. When the porosity exceeds a critical threshold, the effectiveness of the planned operation is directly linked to its absolute value. This observation is further corroborated by widely known data indicating that in 85% of cases, the increase in oil production following secondary treatments is 15–35% lower compared to initial operations due to the gradual and deep-seated clogging of fluid-conducting channels, which leads to a reduction in porosity. Consequently, during treatment operations, it is necessary to ensure high injection rates and introduce specialized additives that stabilize the injected agent under various thermobaric conditions while reducing the interaction time within reservoir systems at both the micro- and macrostructural levels.

The effectiveness of near-wellbore zone treatment with various acid compositions is influenced by the formation thickness, which demonstrates specific threshold

values where the impact of a particular parameter on injection efficiency becomes more pronounced. Tables 1–2 provide a summarized characterization of porosity heterogeneity indicators over a two-year period, based on the compositions employed and the frequency of treatments in the development of the Bashkirian-Serpukhovian reservoirs within the Solikamsk Depression.

Table 1 – Calculated indicators of porosity heterogeneity during primary hydrochloric acid treatment

Composition	Average specific increase in flow rate, t/day Number of wells	$\gamma_{m_{r.max}}$	$\gamma_{m_{r.cp.}}$	$\gamma_{m_{r.min}}$
HCl (12%)	$\frac{3,2}{73}$	0,33	0,45	0,61
DN-9010	$\frac{2,4}{66}$	0,18	0,23	0,306
ZSK	$\frac{1,7}{41}$	0,09	0,23	0,26
ITPS – 708	$\frac{2,7}{50}$	0,28	0,39	0,54
KSPEO	$\frac{3,3}{10}$	0,32	0,37	0,39
NPS-K	$\frac{2,2}{30}$	0,19	0,27	0,36
FLAKSOR-210 (brand P)	$\frac{1,4}{15}$	0,11	0,18	0,29

Table 2 – Calculated indicators of porosity heterogeneity during secondary hydrochloric acid treatment

Composition	Average specific increase in flow rate, t/day Number of wells	$\gamma_{m_{r.max}}$	$\gamma_{m_{r.cp.}}$	$\gamma_{m_{r.min}}$
HCl (12%)	$\frac{2,1}{24}$	0,14	0,25	0,29
DN-9010	$\frac{1,6}{5}$	0,02	0,16	0,174
ZSK	$\frac{1,9}{3}$	0,13	0,17	0,18
ITPS – 708	$\frac{1,1}{3}$	0,12	0,13	0,14
KSPEO	–	–	–	–
NPS-K	$\frac{1,8}{5}$	0,11	0,11	0,17
FLAKSOR-210 (brand P)	$\frac{1,1}{4}$	0,09	0,111	0,116

The interpretation of the obtained results has established that the highest efficiency in primary near-wellbore treatments is achieved using the classical 12% hydrochloric acid composition, for which the maximum attainable porosity heterogeneity index reaches 0.61. Furthermore, calculations of the minimum and average values of γ_(m_r) indicate the absence of significant variations in parameters *x* and *y* that would disrupt the established trend. The depth and effectiveness of HCl (12%) acid penetration into the target treatment interval are closely linked to formation thickness for average porosity values ranging from 0.1 to 0.13 inclusive. In the presence of zones with porosity values exceeding this range, the influence of formation thickness follows an exponential decline, reaching a peak even with minor deviations from the control porosity range. This conclusion is corroborated by a comprehensive assessment of the efficiency of secondary hydrochloric acid treatments under similar geological and physical conditions. The Lorenz coefficient decreased by an average of 47%, accompanied by a more than 1.5-fold reduction in the specific oil production increase. Additionally, the greatest influence of formation thickness on quantitative and qualitative treatment indicators is observed for porosity values between 0.02 and 0.09. Based on the above findings, it is recommended that, to achieve the projected oil production increases when planning treatments with the classical 12% HCl acid composition and selecting optimal candidate wells, additional modeling should be conducted. This modeling should focus on calculating and interpreting the Lorenz coefficients to enhance treatment efficiency and improve candidate selection accuracy.

The composition DN-9010 consists of an aqueous solution of slow-acting hydrochloric acid, corrosion inhibitors, surfactants, and acid-containing solvents. A distinctive feature of this formulation is its high reactivity with asphalt-resin-paraffin deposits of various origins, which accumulate on the rock matrix surface and exhibit high density and stability under reservoir conditions. Another advantage of this agent is its enhanced cleaning effect, which contributes to the restoration of reservoir properties within a radius up to twice that achieved with the classical hydrochloric acid composition under similar geological and physical conditions. As in the previously discussed case, secondary treatment of the near-wellbore zone using DN-9010 results in a decline in technological efficiency. For primary treatment, a strong dependence of injection efficiency on formation thickness is observed within a porosity range of 0.1 to 0.19, beyond which a gradual decline occurs, becoming significantly pronounced after reaching a threshold value of 0.24. During secondary treatment, the porosity range within which formation thickness remains a stable and relevant parameter narrows to 0.07–0.09 on average. This limited variability range may be attributed to the specific characteristics of the acid agent, particularly its cleaning properties, which do not fully manifest at other porosity values due to the restricted volume of intergranular space. Thus, when DN-9010 interacts with the geological medium, the degree of saturation and penetration depth depend equally on both formation thickness and porosity, except

within the calculated threshold ranges. This finding is supported by the significant difference between the maximum Lorenz coefficients for the classical and DN-9010 compositions, exceeding 50% in both primary and secondary treatments.

Discussion. Overall, for the seven compositions analyzed, the minimum and maximum values of porosity heterogeneity indicators range from 0.11 to 0.33 and 0.26 to 0.61 for primary acid treatment, and from 0.02 to 0.14 and 0.14 to 0.29 for secondary treatment, respectively. For the KSPEO agent, the Lorenz coefficient could not be reliably determined in the latter case due to the absence of conducted treatments. Table 3 provides an in-depth assessment of the effectiveness of the formulated recommendations for the application of seven acid compositions, depending on the treatment frequency and porosity variation intervals, within which the influence of formation thickness on treatment efficiency is most significant.

Table 3 – Interpretation results of Lorenz coefficients across the production well stock of the studied field

Composition	Multiplicity of impact		Potential well stock for treatment considering the basic criteria for composition application and obtained results, units.
	Primary	Secondary	
	Range of variation of the parameter m_T		
HCl (12%)	0,1…0,13	0,02…0,09	от 170 до 190
DN-9010	0,1…0,19	0,07…0,09	от 45 до 60
ZSK	0,03…0,05	0,1…0,12	от 20 до 55
ITPS – 708	0,24…0,29	0,15…0,18	от 7 до 12
KSPEO	0,03…0,07	0,05…0,1	от 4 до 8
NPS-K	0,13…0,18	0,12…0,125	от 15 до 20
FLAKSOR-210 (brand P)	0,10…0,14	0,05…0,08	от 3 до 10

Based on the analysis of the existing near-wellbore treatment program and the comparison of planned operations with the obtained data on porosity variation intervals, 34 potential candidate wells were identified. The implementation of treatment in these wells carries risks of failing to achieve the projected technological effect, as well as complications arising from the saturation of non-target zones with acid compositions or their migration into low-permeability areas. For these candidate wells, it is recommended to conduct additional laboratory studies of core samples using X-ray microtomography with a minimum X-ray density threshold of -800 Hounsfield units. This approach would facilitate the identification of both empty and loosely packed material-filled pores, enabling data-driven decision-making based on the response of various compositions to sample treatments.

Conclusion. The study's findings lead to the following conclusions:

− In the context of advancing computer modeling, design, and process monitoring systems, along with the increasing complexity of hydrodynamic channel cleaning technologies in the near-wellbore zone, a priority for subsurface users is

the development of flexible scientific and methodological approaches to account for geological heterogeneity.

− The strong correlation between formation thickness properties and heterogeneity indicators determines the effectiveness of hydrochloric acid treatment and necessitates the identification of numerical values to select the optimal chemical composition.

− Utilizing the obtained porosity heterogeneity coefficients enables the determination of porosity variation intervals, within which formation thickness has the greatest impact on the success of the treatment operation.

− A preliminary assessment of the potential well stock for treatment using the proposed methodology indicates that the total economic effect of the intervention would range from 0.9 to 5 million rubles per year per well, demonstrating the feasibility of integrating the developed scientific and methodological system into the design processes of near-wellbore zone treatment operations.

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ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Ответственный редактор *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Т. Апендиев*
Верстка на компьютере: *Г.Д. Жадырановой*

Подписано в печать 15.10.2025.
Формат 70x90$^{1}/_{16}$. 20,5 п.л.
Заказ 5.

«Central Asian Academic Research Center» LLP
Алматы, Қонаев к-сі, 142