International Journal of Energy Production and Management
https://www.acadlore.com/journals/IJEPM

Development of Innovative Perforation Technology for Enhanced Oil Productivity in Multi-Productive Formation Fields Using Tunnel Well Perforation Methods

Larisa Vazhenina[1*], Ivan Les[2]

[1] Tyumen Industrial University, Department of Economics and Production Organization, 625039 Tyumen, Russian Federation
[2] LLC New Technologies of the North, 625026 Tyumen, Russian Federation

[*] Correspondence: Larisa Vazhenina (vagenina@rambler.ru)

Received: 09-20-2025 **Revised:** 10-05-2025 **Accepted:** 10-20-2025

Citation: L. Vazhenina and I. Les, "Development of innovative perforation technology for enhanced oil productivity in multi-productive formation fields using tunnel well perforation methods," *Int. J. Energy Prod. Manag.*, vol. 10, no. 3, pp. 456–467, 2025. https://doi.org/10.56578/ijepm100308.

Abstract: The main challenge in the development of the oil and gas industry is the reduction in hydrocarbon production using traditional methods due to the increasing share of hard-to-reach oil and gas reserves in the production structure and the insufficiency and practical unfeasibility of innovative resource-efficient methods and techniques for enhancing oil productivity from heterogeneous reservoirs. The objective of this study is to develop a new hydromechanical perforation technique for enhancing oil well productivity from heterogeneous reservoirs of oil and gas fields using an innovative method called "tunnel perforation". The application of the new approach to stimulating heterogeneous reservoirs allows for a significant increase in oil production without the use of explosives. Within a single tripping operation, three technological processes are conducted simultaneously: perforation (primary and secondary), destruction of the cement sheath behind the casing, and acid treatment of the near-wellbore zone. After the completion of the acid treatment, using the initial set of downhole tools, the products of chemical reactions are extracted to the surface without associated material components. The use of tunnel perforation technology allows for effective oil and gas production for subsurface users within a single tripping operation, compared to existing technologies such as cumulative perforation. The system was implemented and tested in three oil fields in different countries, namely, Group of reservoirs A, Group of reservoirs Ach, and Group of reservoirs B. The field test results showed an increase in the reservoir's productivity by 319% for group A, 120.2% for group Ach, and 114.8% for group B.

Keywords: Bottomhole zone; Enhanced oil recovery; Production enhancement; Perforation; Well wall perforation

1 Introduction

In recent years, the Russian industry has been actively implementing import substitution programs. According to them, most of the equipment for oil production and oilfield services is manufactured in Russia. In 2019, the Ministry of Industry and Trade of Russia approved an action plan for import substitution in the oil and gas engineering industry. The document defines technologies and equipment for increasing oil production, the share of imports of which should decrease by 2024 compared to 2018 by at least 25–60% [1]. According to the Strategy for the Development of the Mineral Resource Base of the Russian Federation until 2050, the development of geological exploration, reproduction, and utilization of the country's natural resources is impossible without improving the legislative framework for regulating subsoil use and enhancing the participation of small and medium-sized enterprises.

An analysis of global experience shows that the task of reproducing the raw material base for oil production is addressed through the implementation and improvement of two state programs: increasing reserves by exploring new fields and enhancing recoverable reserves through the modernization of oil extraction based on innovative technologies and the industrial application of modern tertiary oil recovery methods (EOR) [1]. In many countries engaged in oil production (for example, the USA, Canada, Venezuela, Norway, China, Indonesia, Kazakhstan, and others), significant economic incentives, including tax holidays, are offered for the implementation of the abovementioned state programs at the stage of industrial testing and the introduction of modern methods for increasing crude oil production. This is due to the high costs and risks at the initial stages of testing EOR projects because of the lack of or absence of experience in their application.

However, after widespread implementation and achieving large volumes of oil production, the cost of these technologies significantly decreases, making them accessible to the entire oil and gas industry. The efficiency of raw material extraction from formations depends on modern methods of deposit development. Today, the level of hydrocarbon extraction is considered insufficient, as their consumption continues to grow. The average oil recovery factor around the world varies from 25% to 40%. For some regions, this figure is as follows: Latin America and Southeast Asia: 24%–27%; Iran: 16%–17%; USA, Canada, Saudi Arabia: 33%–37%; CIS countries and Russia: up to 40%. The indicator is directly related to the volume of raw material stocks and the methods used. To increase the efficiency of extracting raw materials from formations, it is necessary to introduce modern technologies to increase oil recovery. The main direction of development in oil production is increasing its recovery rate, which significantly extracts additional volumes of hydrocarbon raw materials.

Relevant research in the development of the oil industry includes creating innovative technologies to enhance oil recovery during the exploration and exploitation of oil fields. The development of EOR technologies is multifaceted and includes both chemical and physical methods. Leading countries such as the United States, China, Russia, Saudi Arabia, and Norway invest significant resources in R&D to develop innovative solutions aimed at increasing the efficiency of oil production and minimizing the negative impact on the environment. Key companies in these countries are actively developing and implementing advanced technologies, UAE Energy Strategy [1], which allows them to maintain leadership in the industry. This is associated with the increasing cost of developing new technologies and the complexity of their implementation.

In this regard, there is a growing interest in innovative technical solutions to EOR, because traditional oil production methods do not allow for the extraction of residual reserves, averaging 55%-75% of the initial deposits in the reservoir. Methods of increasing oil yield at the Zapolyarnoye field through the use of chemical and mechanical means are considered by Vagenina [2]. For Russia, an important step could be the implementation of international experience, including scaling up successful technologies through public-private partnerships and attracting investors. The use of new technologies will allow for obtaining additional volumes of hydrocarbon raw materials and ensuring maximum results in oil production.

A literature review show diverse technologies being employed to boost oil recovery and optimize well productivity. These include various types of perforation, chemical treatments, mechanical means of stimulating the near-wellbore area, as well as advanced digital technologies. Both Russian and foreign authors emphasize several key directions in their research. Russian researchers have focused primarily on practical case studies and innovative solutions directly applicable in regions. For instance, Shakurova and Shakurova [3], Karimov and Toktarbay [4], and Mahajan et al. [5] conducted investigations into the efficiency of hydraulic fracturing under challenging geological conditions, particularly in mature and long-established industrial districts of Russia. Their findings highlight the necessity of individualized approaches tailored to specific features of each deposit, emphasizing the importance of detailed analysis of physical-mechanical properties of rock formations and optimally designed fracture configurations.

Separately, traditional processing methods like shaped-charge perforation were examined. Studies by Chernyshov et al. [6] and Zhang et al. [7] demonstrated how hydroabrasive perforation influences water flooding coverage of reservoirs, confirming the beneficial effect of this technology on oil recovery in particular regions. There is also a notable rise in theoretical studies focusing on fundamental mechanisms and universal models. For example, Chernyshov et al. [8], Nurov et al. [9], and Huque et al. [10] introduced a novel technique for assessing the depth of explosive charge penetration, allowing deeper insights into the mechanism of rock fragmentation and its influence on well productivity.

Another noteworthy study was carried out by a group of researchers led by Doskazieva and Imangalieva [11], Patel et al. [12], Thomas [13], and Shaikhah et al. [14]. They investigated the application of organic acid solutions to enhance oil recovery in heterogeneous reservoirs. The authors highlighted positive effects of chemical treatments that contribute to increased oil production, but also noted limitations associated with corrosion activity and potential sediment formation.

A comprehensive overview of existing methods for enhancing oil recovery has been performed and reported by Adeel et al. [15], Yang et al. [16], Guo et al. [17], Kuleshov et al. [18], and Hamdi et al. [19]. They shared the same observation on a rising interest in physical and chemical stimulation techniques, including the injection of CO_2, methane, and nitrogen [20–22]. According to them, the success of these methods depends heavily on understanding the physical properties of the reservoir and choosing appropriate technologies accordingly.

Other groups of scientists, such as Zhang et al. [23], Nurov et al. [9], and Al-Obaidi et al. [24], focused specifically on innovative techniques for stimulating low-permeability dense reservoirs. They demonstrated the effectiveness of combining vertical and inclined wells followed by multizone hydraulic fracturing. Furthermore, researchers like Tang et al. [25], Wu et al. [26], Gong et al. [27], Luo et al. [28], and Cao et al. [29] showed that integrated numerical modeling of combined hydraulic fracturing and acidizing can accurately predict expected increases in oil production in unconventional reservoirs. Some authors, such as Zhang et al. [23], Ahmadi et al. [30], and Khaliullin [31], explored the possibilities of implementing digital technologies in oil production to extract additional volumes of hydrocarbons. For example, Duplyakov et al. [32] developed a comprehensive methodology for calculating the steady-state mode of oil production using a suspension filtration model considering non-Newtonian rheology, particle transport, inflow from the reservoir, and geomechanical factors.

Dmitrievsky et al. [33] analyzes risks associated with the use of artificial intelligence technologies in the oil and gas sector. Barros-Galvis et al. [34] investigated the impact of fluid dynamics on oil production in naturally fractured reservoirs. Al-Kayiem and Jamil [35] and Jamil and Al-Kayiem [36] conducted fundamental research on oil-water flow emulsion in boreholes using computational fluid dynamics (CFD) simulations in attempt of downhole oil/water separation and re-dumping of produced water to enhance the well productivity.

The literary analysis demonstrates substantial progress in research on enhancing oil production and refining perforation methods. Russian specialists emphasize local experience and applied developments, while international authors strive to expand theoretical knowledge boundaries and create globally applicable solutions. Combining the expertise of foreign and domestic authors may lead to significant achievements in increasing oil production and optimizing drilling and well maintenance procedures.

The list of technologies used to enhance oil recovery/productivity in modern conditions is given in Table 1. Current developments in science and engineering on oil production demonstrate growing interest among researchers towards enhanced oil recovery (EOR) and improvements in perforation techniques for enhanced productivity.

Table 1. Enhanced oil productivity and recovery technologies and methods

Methods and Techniques	**In Russia**	**Abroad**
1. Multistage hydraulic fracturing (Hydraulic Fracturing)	Hydraulic fracturing (FRACKING) technologies are actively used to EOR in old and low-permeability fields such as the Bazhenov Formation [3–5, 37]. Work is underway to adapt technologies to difficult geological conditions (for example, low-permeability and hard-to-recover hydrocarbons) [6–9, 37].	In the international arena, MSHF technologies continue to improve, including the use of environmentally friendly components and liquid recycling. In the USA and Canada, micro seismic monitoring technologies are actively used to improve the quality of hydraulic fracturing [10–13, 37].
2. Chemical extraction of crude oil (Chemical EOR)	Use of polymer and alkaline solutions to enhance the extraction of crude oil; creation of Russian chemical reagents (surfactants, polymers, alkalis) to reduce dependence on imports, especially in the context of sanctions [11–13, 38–41].	Implementation of nanotechnology, including nanoparticles, to improve the penetration of chemical reagents into porous media [14]. Development of new classes of surfactants (surfactants) resistant to extreme conditions (high temperature, salinity) [19, 30, 38–41].
3. Gas methods for enhancing oil recovery (Gas EOR)	Carbon dioxide injection (CO_2-EOR) is actively developing as a method of enhancing oil recovery and a method of carbon capture (CCUS - Carbon Capture, Utilization, and Storage); the use of nitrogen and natural gas to increase reservoir pressure [20–22].	
4. Thermo-chemical methods	Development of thermochemical impact technologies to improve oil mobility in high-viscosity formations; use of hot gases and steam-gas mixtures in Western Siberia [18].	Implementation of steam-thermal impact technologies (Steam-Assisted Gravity Drainage, SAGD), especially in Canada, for the production of heavy oil. Combined methods include thermochemical and steam exposure [26].
5. Digitalization and process modeling	Application of artificial intelligence and machine learning to optimize perforation parameters and reagent selection; development of digital well twin technologies for more accurate efficiency forecasting, EOR [23, 30, 31, 33].	Using big data and artificial intelligence to analyze reservoir behavior and manage development processes [33].
6. Innovative approaches to well perforation	Implementation of laser perforation technologies to improve accuracy and efficiency; application of jet perforation (Jetting Technology) to minimize formation damage; use of ecological chemical methods; application of microbiological methods (use of microorganisms for biodegradation of oil components and increase of their mobility) [30].	Application of microbiological impact (genetic modification of microorganisms to increase the efficiency of EOR; development of bioreactors for the production of bioregenerating reagents). Integration of ultrasonic generators into reagent injection systems; research on the effect of ultrasound on oil and rock parameters. Development of biodegradable reagents for EOR; research on the use of renewable components in reagent compositions [33].

An unaddressed issue in this area of research is the irrational use of oil and gas reserves, as well as increasing the efficiency of geological and technological measures aimed at extracting additional volumes of hydrocarbon raw materials. The standard solution in most cases involves repeated cumulative perforation followed by stimulation operations to enhance oil production (hydraulic fracturing, acid treatment).

The literature suggests that one of the challenges in the development of the oil and gas industry is the reduction in oil production volumes using traditional methods, which is associated with an increase in the share of hard-to-reach hydrocarbon reserves and the high cost of existing technological solutions for their extraction. The global number of active oil wells with a production rate of less than 30 m^3/day accounts for about 50% of the total well fund. Solving this problem is possible through the development and implementation of innovative resource-efficient perforation and hydraulic fracturing (HFR) technologies. This study aims to develop a hydromechanical perforation technology for EOR from heterogeneous reservoirs of oil and gas fields based on the application of a resource-saving set of measures.

2 Perforation Identification and Research Problem Formulation

The process of developing an oil field from the perspective of the product life cycle includes three phases, each requiring corresponding investment costs, which should reflect high economic efficiency if such a project is implemented.

The first phase of oil extraction involves utilizing natural reservoir energy, including Rock and Fluid Expansion, Solution gas drive and gas cap drive, Aquifer bottom drive, oil bank, and Gravity Drainage.

The second phase entails applying secondary methods of maintaining reservoir pressure through water or gas injection, enabling the extraction of no more than 30%-40% of initially established oil reserves. The inefficiency of these methods is due to the heterogeneity of different rocks within the productive layer, which is characterized by shale structure, leading to slow fluid filtration, thus reducing the oil recovery factor.

The third phase of the reservoir's lifecycle, where employing EOR techniques provides the highest economic efficiency after exhaustion of natural reservoir energy from the first phase (Solution gas drive and gas cap drive, Aquifer bottom drive, oil bank, and Gravity Drainage) and the second phase involving water injection and gas injection for maintaining reservoir pressure.

The main purpose of perforation is to ensure the flow of oil and gas from the formation into the well. Perforation is the process of creating channels (perforations) in the casing and cement ring that connect the well to the productive formation. The following types of well perforation are distinguished:

I. Perforation with cumulative charges. Domestic and Western service companies predominantly use this method. Optimization of perforation parameters involves selecting optimal characteristics (depth, diameter, number of channels), considering the properties of the reservoir and the design of the well. Quality control of perforation is based on the need for geophysical studies to assess the effectiveness of perforation and identify possible perforating technologies at fields.

II. Hydrofrack perforation. A secondary method of opening up productive formations where destruction of the casing wall, cement stone, and rock occurs using high-speed water jets containing abrasive inclusions. Quartz sand or artificial ceramic sand of small fractions is used as an abrasive material.

III. Complex plastic perforation. Technology of non-explosive opening and treatment of near-well zones of productive formations. When this technology is applied, paired longitudinal slots are preliminarily formed in the productive interval with washout cavities in the near-well zone of the formation using a perforator. Through special technological openings of the perforator–water jet nozzles and circulation valves – the injection of hydrochloric acid or clay acid into the formation takes place. After chemical reaction processing, the products of the reaction are developed through washing out and pumping out the liquid.

IV. Hydromechanical slot perforation. It allows avoiding complications due to the absence of impact on the production casing and formation. Slot cutting is performed by a rolling disc with stepwise pressure increase at the wellhead from 1 MPa to 6–7 MPa with a step of 1 MPa.

A main type of work in the practical implementation of tunnel perforation technology is the application of chemical reagents by injecting them into the reservoir. This allows reducing interfacial tension and oil viscosity, as well as increasing the permeability of the bottomhole formation zone (BFZ). The use of various acid mixtures allows dissolving part of the bottomhole formation zone and increasing its permeability [11–14]. Figure 1 shows the process of conducting acid treatments using reactive acid jets.

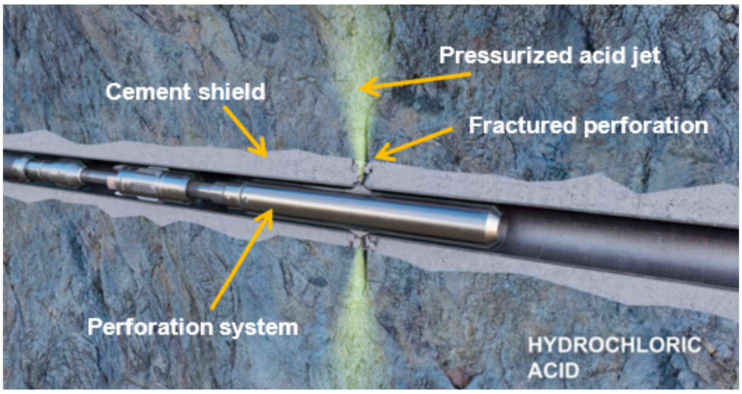

Figure 1. Image of the TPS using a reactive acid jet perforation [13]

Thus, when hydrochloric acid interacts with carbonate rocks, salt solutions, carbon dioxide (CO_2), and water are formed, which are easily extracted during well operation, creating permeability channels. Under conditions of extremely high temperatures of 155°C, the gaseous state of the released carbon dioxide has a positive effect on reducing the viscosity of oil [20–22].

In some cases, jelly mixtures are formed in the BFZ, or poorly soluble sediments fall out, which reduces the permeability of the formation or leads to blockage of channels, reducing the effectiveness of acid treatment. Resumption of well operation as a result of their filling using hydrogen chloride exposure is carried out on the basis of a one-time injection of a standard amount of working solution into the injection well, which is calculated for each specific case.

Regular sulfuric acid treatment forms rims of alkylated sulfuric acid waste in the bottomhole zone. However, among other chemical methods used to increase oil flow, concentrated sulfuric acid effectively reacts with the formation composition, creating chemical and thermodynamic effects [11].

The most widely used acidic compositions are based on mud acid with the addition of fluorine for the treatment of low-permeability terrigenous reservoirs. The most important parameter of such acidic solutions when treating bottomhole formation zones (BFZ) is the speed of their reaction with the rock.

During acid treatment, loosening and movement of quartz and clay particles are observed, which can lead to blockage of the collector with its own particles. The interaction of acidic compositions with clayey sandstones is characterized by complexity and requires additional research [33].

Methods of increasing the permeability of the formation and the bottomhole zone are widely used in the development of oil and gas fields. The reason for this is the clogging of the bottomhole zone caused by the accumulation of solid and swollen rock particles, heavy resinous oil residues, salts precipitating from formation water, paraffin deposits, hydrates (in gas formations), etc. Mechanical, chemical, and physical methods are used to increase the permeability of the formation and the bottomhole zone [3–5].

An analysis of the technologies used made it possible to identify the main priorities of scientific and technological development in the field of geological exploration of the subsoil, prospecting, evaluation, and exploration of mineral deposits:

I. Development of technologies aimed at increasing the EOR factor and reducing its losses during extraction and processing, including through the use of methods of geological and technological mapping of debris products after acid stimulation and perforation.

II. Development and improvement of efficient technologies for cost-effective extraction and processing of low-quality and multicomponent hydrocarbons, and human-caused waste.

III. Formation of the federal research center for mineral raw materials technologies for the creation and improvement of technologies for producing various types of deposits, the introduction and scaling of technological chains for developing deep processing products of solid minerals, including their disposal.

3 Materials and Methods

Advanced perforation technologies are required in the oil and gas wells for enhanced productivity. The reason for this is the "clogging" of the bottomhole zone by filling the pores with solid and swollen rock particles, heavy resinous oil residues, salt precipitation out of reservoir water, paraffin deposits, and hydrates (in gas formations). More than 60% of the inactive well stock is unprofitable due to low accessibility of hydrocarbon reserves and high cost of existing technological solutions for oil extraction. In this study, the authors propose a new method of hydromechanical stimulation of heterogeneous reservoirs in Russia and abroad using tunnel perforation technology to enhance oil recovery.

TPS is a conservative way of perforation that creates injectivity between the well and formation by cutting long slots or tunnels in the well casing with round cylinders.

The well perforation system proposed by the authors is integrated into a single assembly and includes: a hydromechanical tunnel perforator; a rotary-type packer device; and a jet pump (ejector-type device). The perforator is equipped with jet nozzles that erode cement stone, forming caverns in the wellbore.

The practical implementation of the proposed well perforation technology using a universal hydromechanical tunnel perforator is carried out as follows (Figure 2).

The procedure includes the following steps:

i. The perforation system is lowered into the well.

ii. The perforator is fixed on the tubing string and lowered to the perforation interval. Logging or mechanical CCL is used for depth matching. The pump unit creates initial pressure, activating the round cylinders.

iii. The cylinders cut the casing walls, forming long slots in the well casing.

iv. The working fluid is supplied to the system.

v. Jet nozzles erode the cement ring and rocks, forming caverns in the wellbore all along the slots.

vi. Each trip in and out of the well using the nozzles of the tunnel perforator involves pumping acidic solutions.

vii. After the chemical reaction is complete (approximately 6 hours), the products of the acid reaction are extracted using a jet pump 8. A special return mechanism ensures the closure of the cylinders.

The features of TPS are as follows:

i. Geophysics or casing collar locator regulates depth.

ii. The activation mechanism of the cylinders is based on hydraulic force, which causes the cutting elements to rotate.

iii. Round cylinders are less likely to get stuck because there is no friction in the casing when cutting metal.

iv. Open hole operations are possible.

v. 7" and 5" perforators are available for different casings.

The main parameters of tunnel perforation are presented in Table 2.

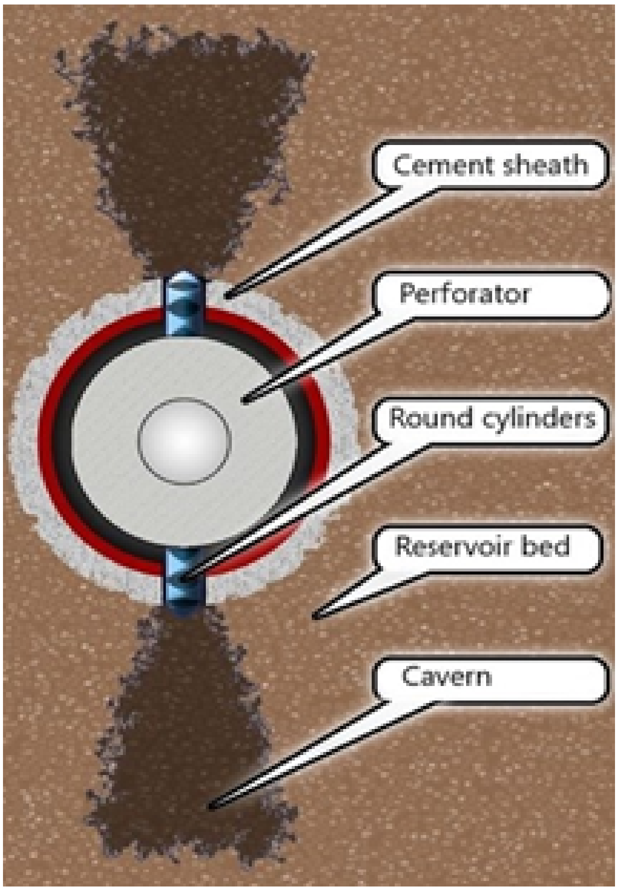

Figure 2. The operation process of tunnel perforation [37]

Table 2. Key parameters of our model

Parameter	Value
The length of the caverns, ft	1.64–29.5
The width of the caverns, in	0.47
Total length of the perforation, ft	131
Amount of slots on one interval, depending on requirements	2–4
The penetration of the jet nozzle along the entire length of the slot, ft	9.8

The complex of operations to enhance oil recovery within the proposed tunnel perforation technology is conducted without the use of explosives (only water is used). Increased oil production is achieved by creating additional perforation slots, up to 33 m, in a single trip in the casing. This technology allows for simultaneous perforation and hydrochloric acid treatment through the perforator in a single operation, which reduces the degradation of the cement stone.

To extract hydrocarbons from complex geological structures, it is often necessary to simultaneously exploit several oil or gas condensate-bearing formations with different characteristics (for example, reservoir pressure, porosity, permeability, saturation pressure, viscosity, hydrocarbon reserves, etc.). According to many Russian and foreign experts, one of the most effective methods of increasing hydrocarbon production today is hydraulic fracturing technology. However, the specific conditions for the development of multilayered, complex formations in Western Siberia fields complicate the direct use of this technology. To involve heterogeneous formations in the development of multi–layered formations, it is proposed to use a complex multistage operation-phased hydraulic fracturing.

The methodology for evaluating the effectiveness of hydraulic fracturing uses a series of equations [42].

The increase in productivity of oil-bearing formations with different filtration and capacitance characteristics as a result of phased hydraulic fracturing is calculated using the Binder and Raymond equations or an alternative formula given by Eq. (1).

$$\frac{J}{J_0} = \frac{\frac{1}{k}\ln\left(\frac{R_k}{r_d}\right) + \frac{1}{k_d}\ln\left(\frac{r_d}{r_c}\right) + \frac{1}{k_d}C_2}{\frac{1}{k}\ln\left(\frac{R_k}{L}\right) + \frac{1}{k_2}\ln\left(\frac{L}{r_d}\right) + \frac{1}{k_1}\left[\ln\left(\frac{r_d}{r_c}\right) + C_2'\right]} \tag{1}$$

where, J_0, and J denote the productivity of the well before and after hydraulic fracturing, respectively, in m^2; k is the permeability of the remote part of the reservoir, (m^3); k_1 is weighted average permeability of the clean part of the formation crossed by a fracture, (m^3); k_2 is the average permeability value of the contaminated part of the formation crossed by the fracture, (m^3); k_d is diffusion coefficient, (m^2/sec); R_k is the radius of drainage area, m; r_c is the borehole radius, (m); r_d is radius of the colmatation zone, (m); L is the Fracture half-length, (m); C_2, $C\prime_2$ are the change in resistance as a result of perforation before and after hydraulic fracturing, respectively, is dimensionless.

If the productivity of the oil reservoir exposed by the well after hydraulic fracturing is equal to J_i, and before the event was J_{0i}, then the total productivity of the well after the event is determined by Eq. (2). The calculation of the change in the total productivity of the well as a result of hydraulic fracturing is conducted by Eq. (3).

$$J = \frac{\sum_i J_i \Delta p_i}{\Delta p} \tag{2}$$

$$\frac{J}{J_0} = \frac{\Delta p_0 \sum J_i \Delta p_0}{\Delta p \sum J_{0i} \Delta p_{0i}} \tag{3}$$

where, Ji is the productivity of the i-th oil reservoir (i÷1-N) penetrated by the well after HFR, (m^2); $\Delta p\,(\Delta p_0)$ is the wellbore pressure drawdown after hydraulic fracturing (before hydraulic fracturing), (MPa); $\Delta p_i\,(\Delta p_{0i})$ is the pressure drawdown of the i-th interlayer after hydraulic fracturing (before hydraulic fracturing), (MPa). J/J_o is the change in well productivity after hydraulic fracturing (m^2).

When developing multilayer oil and oil and gas condensate formations, the uniformity of reserves extraction from the developed formations becomes a key indicator. The equality of the selection rates of the current reserves in each reservoir estimates an uneven oil saturation distribution caused by uneven production rates and well placement.

The rate of selection N_i is determined by the ratio of accumulated oil extraction from the i-th reservoir at time t after measures to increase oil recovery and current reserves W_i in the drainage area of this well at the time of hydraulic Eq.(4). Compliance with the equality of selection rates and ensuring uniform production of reservoir reserves can be achieved by Eq. (5).

$$N_i = \frac{\int_{t_0}^{t} q_i(t)dt}{W_i} \tag{4}$$

$$N_1 = N_2 = \ldots. = Ns \tag{5}$$

where, $q_i(t)$ is the oil productivity of the i-th reservoir, (barrels per day); t_0 is the moment of putting the well into operation after hydraulic fracturing, days; N is the number of perforation holes, units; and s is the number of reservoirs.

To find the maximum fracture width (ξ) using calculations of the penetration of fracturing fluid (ω_0) into the formation, considering the volume of liquid that has seeped through the fracture walls into the formation and the volume of the fracture itself, you can use the Eq. (6).

$$\omega_0 = \frac{4(1-2v)(1+v)\left(\Delta \mathrm{P}_c - P_{\mathrm{b.g.}}\right)}{3E} \left(\frac{V_f q \mu}{2\pi^2 h^2 m \kappa_n P_{\mathrm{b.g.}}}\right)^{0,5} \tag{6}$$

The fracture half-length L is determined by the nonlinear Eq. (7):

$$qt = \frac{4hL(1-2v)(1+v)\left(\Delta \mathrm{P}_c - P_{\mathrm{b.g.}}\right)}{3E} \left(\frac{4L\xi q \mu}{2\pi^2 h \kappa_n P_{\mathrm{b.g.}}}\right)^{0.5} + 4L\xi m h \tag{7}$$

where, ω_0 is the maximum fracture width, (m); v is the Poisson's ratio; E is Young's module, (Pa); q is the burst fluid injection rate, $\left(\mathrm{m}^3/\mathrm{h}\right)$; m is the reservoir porosity, $\Delta \mathrm{P_c}$ - repression of the formation, (Pa); $P_{b.g}$ is the lateral mountain pressure, (Pa); V_f is the rupture fluid volume, $\left(\mathrm{m}^3\right)$; ξ is the maximum fracture width, (m); μ is the viscosity of reservoir fluid, ($\mathrm{Pa} \cdot \mathrm{sec}$); h is the thickness of the productive reservoir, (m); and K_n is the permeability coefficient, (m^2).

The width of the closed fracture (ω) is expressed by Eq. (8), and the fracture half-length ($\mathrm{L_{II}}$) filled with proppant is $\mathrm{L_{II}} = 0.9$ L.

$$\omega = 1,1 \frac{v_n \omega_0}{v_f} \tag{8}$$

The permeability of a fracture, κ_{fr}, is determined from the Eq. (9):

$$\kappa_{\mathrm{fr}} = \frac{\omega^2}{48 \cdot 10^4} \tag{9}$$

The volume-weighted average permeability of the borehole zone of the reservoir (κ_{II3II}) is calculated by Eq. (10):

$$\kappa_{NWZ} = \frac{\kappa_n \cdot (V_{pl} - V_f) + \kappa_{\mathrm{fr}} \cdot V_f}{V_{pl}} \tag{10}$$

where, ω is the closed fracture width, (m); V_n is the volume of propping agent, $\left(\mathrm{m}^3\right)$; V_f is the fracture volume, $\left(\mathrm{m}^3\right)$; K_{fr} is the fracture permeability of hydraulic fracturing, $\left(\mathrm{m}^2\right)$; $\mathrm{K}_{\mathrm{NWZ}}$ is near-wellbore zone of the reservoir (NWZ) permeability, $\left(\mathrm{m}^2\right)$; $V_{pl}=\pi L^2 h$ is the volume of the near-wellbore zone penetrated by the fracture, $\left(\mathrm{m}^3\right)$.

The potential flow rate of the well after hydraulic fracturing operations, obtained using a multizone flow pattern and considering the perforation of the well before hydraulic fracturing, is determined by Eqs. (11)–(13).

$$Q_{p2}=86400\cdot\frac{-A_2+\sqrt{A_2^2+4B_2\left(P_p^2-P_z^2\right)}}{2B_2} \tag{11}$$

$$A_2=\frac{\mu z P_{at}T_{pl}}{\pi h T_{st}}\left(\frac{1}{k_1}\ln\frac{R_k}{L}+\frac{1}{K_{NWZ}}\ln\frac{L}{r_c}+\frac{1}{K_{NWZ}}\frac{\pi r_0}{2\omega}\right) \tag{12}$$

$$B_2=\frac{\rho_{st}ZP_{at}T_{pl}}{2\pi^2 Ih^2T_{st}}\left(\frac{1}{r_c}-\frac{1}{R_k}+\frac{\pi^2r_0^2}{12\omega^2}\right) \tag{13}$$

where, Q_{p2} is the potential well productivity after hydraulic fracturing, $(\mathrm{m}^3/$ day); A_2 is a coefficient that accounts for the geometric and physical parameters of the fracture, $(\mathrm{m}^2/$ day); B_2 is a coefficient that accounts for fluid viscosity and other physical parameters, $\left(\mathrm{Pa}\cdot\mathrm{sec}/\mathrm{m}^2\right)$; P_p is the reservoir pressure, (Pa); P_z is the bottomhole pressure, (Pa); z is a supercompressibility factor, dimensionless; P_{at} is the atmospheric pressure, (Pa); T_{pl} is the reservoir temperature, (K); T_{st} is a standard temperature, K ; r_0 is the radius of the perforation holes, (m); ρ_{st} is the gas density under standard conditions, $\left(\mathrm{kg}/\mathrm{m}^3\right)$; and I is macro-roughness coefficient.

For the successful implementation of phased hydraulic fracturing in order to optimize hydrocarbon production, a theoretical justification considering these parameters is extremely important. Calculation of hydraulic fracturing technological parameters (length, width, crack conductivity) based on the filtration and capacitance properties of productive formations and hydrocarbon reserves will ensure equal sampling rates.

The methodology for calculating the parameters of cracks and productivity of oil wells during phased hydraulic fracturing at complex oil facilities will ensure uniform drainage of formations with initially different reservoir properties. The technology of hydraulic fracturing in shallow and horizontal wells, which increases the flow of fluids into the horizontal shaft from cracks, was developed earlier and described in detail in relevant publications [42]. When considering the use of acid treatments and increasing the efficiency of acid compositions, the subsurface user pursues similar objectives, namely, acid treatment with the greatest increase in production within the exploited productive area.

Thus, in this study, the authors propose one of the methods to solve the problem of enhancing oil recovery from heterogeneous reservoirs using tunnel perforation technology. This technology ensures additional oil inflow while stabilizing the wellbore without altering the filtration properties through such actions as well as killing, isolation of already involved sections, and saturation of reservoirs with solutions. The proposed tunnel perforation system (TPS) allows for a significant increase in the efficiency of hydraulic fracturing (HFR) by performing up to 20 stages of perforation/HFR by a single work crew.

The tests of the proposed technology in real oil fields were conducted within the framework of contracts with “Meta Energy Inc.” (Kazakhstan), “NNK Company Trade”, JSC NC “KazMunayGas”, and “Petrofaum” (Egypt), and have been characterized by high economic and technological efficiency.

4 Results and Discussions

The results of staged hydraulic fracturing in vertical wells depend on many factors, such as existing conditions, the skin factor, the presence of perforations, the well-reservoir connection, and more. As part of the application of the WCS system, a significant potential lies in the ability to carry out an unlimited number of perforation/hydraulic fracturing cycles and highly effective acid treatments. The use of this arrangement solves the problem of increasing oil recovery without increasing the cost of the operation. The use of this system tunnel perforation solves the problem of attracting many contractors (perforation, poker service, cattle for filling out the interval of previously performed hydraulic fracturing, cattle for normalization after all operations) [37]. The advantages of tunnel perforation are as follows:

• Easy to transport through customs.
• No destructive effect on the casing.
• High-quality caverns.
• Large formation opening area.
• Low operating pressure during hydraulic fracturing.
• No risk of clogging the wellbore zone.

The quantitative assessment of the advantages of tunnel perforation compared to cumulative perforation is reflected in Table 3.

The TPS allows for a variety of perforations and hydraulic fracturing in a single lifting operation carried out by a cattle crew. After completing all operations, no additional costs are required. When completing horizontal sections of wells, there is no need to use MGRP couplings, but as a need for additional milling work in the future. Figure 3 shows the tests using water jet technology. In real conditions, water is replaced with acidic components at the well.

The result of applying this technology is formed from existing conditions, the skin factor, perforation holes, well/reservoir communication, etc. As part of the work using an acid-treated perforator, the limitlessness of the perforation/reperforation stages and highly effective acid treatments has great potential. The use of this arrangement solves the problem of increasing oil recovery without increasing the cost of the operation, while significantly increasing the technological effect.

Table 3. The quantitative assessment of the advantages of tunnel perforation compared to cumulative perforation

Parameter	Tunnel Perforation	Cumulative Perforation
Opening area per linear foot of casing, ft^2	0.72–1.71	0.079–0.187
Depth of penetration into the formation, ft	1.64–3.28	0.49–2.46
Inlet geometry, in	Slot width 0.39-0.47	Hole with a diameter up to 0.91

Figure 3. Laboratory tests using water jet technology [37]

Table 4. Comparative assessment of the effectiveness of tunnel and cumulative perforation

Indicators	Cumulative Perforation	Tunnel Perforation	Enhanced Productivity
	Group of reservoirs A		
Liquid production rate, barrels/day	118.4	207.3	
Water cut, %	15.2	23.7	
Oil production rate, barrels/day	35.5	113.2	319%*
	Group of reservoirs Ach		
Liquid production rate, barrels/day	35.9	275.3	
Water cut, %	4.7	34.4	
Oil production rate, barrels/day	25.2	55.5	120.2%*
	Group of reservoirs B		
Liquid production rate, barrels/day	60.5	165.6	
Water cut, %	7.8	19.2	
Oil production rate, barrels/day	29.6	63.6	114.8%*
Cost per well, thousand dollars	65.7	18.9	
Number of hours	130	52	

*The effectiveness of implementing the proposed technology exceeds traditional methods by the percentage specified.

The evaluation of the effectiveness of TPS technology compared to cumulative perforation is presented in Table 4 [37].

Analyzing the results presented in Table 4 after performing various types of perforation on heterogeneous reservoirs, it can be noted that TPS technique is significantly more effective compared to cumulative perforation. The enhancement is 319%, 120.2% and 114.8% for the tested reservoirs, Group A, Group Ach, and Group B, respectively. For example, the cost of conducting a set of operations on one well and the number of working hours are 3.5 and 2.5 times lower, respectively. The oil production rate for different groups of reservoirs, on average, after tunnel perforation is more than three times higher.

A series of tests with representatives of oil companies and scientific institutes has proved the practicality and viability of the proposed technology. The developed TPS technology is based on a symbiosis of possibilities for perforation and hydraulic fracturing and allows, if desired, to carry out more than five perforations plus hydraulic fracturing, without performing additional fracking and without removing the tool from the well [37].

When using acid treatments, a hydromechanical perforation system is proposed that combines several stages of oil recovery improvement into one, namely: perforation (reperforation). Acid treatment of the interval is carried out by creating a reactive acid jet with significant penetration of acids into the depth of the downhole zone, thereby increasing the effectiveness of oil recovery measures. In borehole conditions, water is replaced with acidic components.

The high export potential of the proposed technology makes it possible to produce competitive products based on an internationally patented range of services and to sell them in foreign markets due to the combination of production, innovation, human resources, and market potential of the company. The proposed innovative technology is planned to be used abroad. The first tests were conducted in Egypt under existing contracts. For example, one of the perforation jobs on the Petrofaum field in Egypt demonstrated the effectiveness of tunnel perforation and subsequent professionally cleaning. Prior to the application of this technology, all wells on the Petrofaum field produced oil only with the use of hydraulic fracturing (HFR). After the tunnel perforation work was completed, the customer began oil production.

The demand for the product outside the Russian Federation can ensure the involvement of new business partners and increase the favorable investment climate in the country. It is planned to spend more than 80 million rubles on research and development of technology, which will also increase the level of innovation activity in the country.

The TPS technology developed by the authors has significant competitive advantages over the domestic and foreign methods offered in the oilfield services market, which are as follows:

• The equipment with cutting elements creates longitudinal channels that increase the injection of oil into the reservoir.

• The complexity of work on one equipment includes hydrochloric acid treatment (has acid resistance up to 15% of concentration), development, perforation, and flushing of the reservoir.

• Replacement of expensive flexible tubing and hydraulic fracturing services reduces cost and speeds up work.

• Absence of high explosive (explosives).

• Use in high-risk areas does not require multiple permits.

• Multi-cycle perforation and repair and insulation work (RIW) in one lifting and lowering operation (processing up to 20 intervals of perforation + BFZ/RIW).

• Application in cemented and non-cemented production columns 102–178 mm.

5 Conclusions

The stock of operating oil wells in Russia and some other countries, with a flow rate of less than 30 m^3/day, is about 50% of the total well stock. Thus, the development and implementation of new methods and technologies for highly effective stimulation of heterogeneous reservoirs to enhance productivity is an important task for the oil and gas industry.

The introduced tunnel perforation technology for wells (TPS) in this study has demonstrated its practical feasibility during field tests on the potential customer's wells. This technology is an environmentally friendly method for the effective extraction of scarce types of useful minerals, and the complex of works proposed by the authors of the tunnel perforation includes resource-saving measures that allow for a significant technological and economic effect. The field tests show an enhanced oil production in three testing fields by 319%, 120.2%, and 114.8% for fields Group A, fields Group Ach, and fields in Group B, respectively.

The demand for this innovative technology both outside the country and within the territory of the Russian Federation can ensure the involvement of new business partners, improve the favorable investment climate, and increase the level of innovation activity in the oil and gas industry.

Author Contributions

All the authors contributed equally to the present work. Conceptualization, V.L. and L.I.; methodology, V.L.; validation, V.L. and L.I.; formal analysis and investigation, V.L. and L.I.; writing—original draft preparation, V.L.; writing—review and editing, V.L.; visualization, V.L. and L.I. All authors have read and agreed to the published version of the manuscript.

Data Availability

Not applicable.

Acknowledgements

We would like to thank Tyumen Industrial University, Russia, for supporting the publication of this work.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Uae energy strategy. Emirates News Agency (WAM). Accessed on Oct. 27, 2025. https://www.wam.ae/en/details/1395303174303

[2] L. Vagenina, "Selection and evaluation of technologies for oil rim preparation of the zapolyarnoye oilfield," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 87, p. 052032, 2017. https://doi.org/10.1088/1755-1315/87/5/052032

[3] A. F. Shakurova and A. F. Shakurova, "Study of geological and technological factors on the efficiency of hydraulic fracturing," *J. Phys.: Conf. Ser.*, vol. 1333, no. 6, p. 062025, 2019. https://doi.org/10.1088/1742-6596/1333/6/062025

[4] D. Karimov and Z. H. Toktarbay, "Enhanced oil recovery: Techniques, strategies, and advances," *ES Mater. Manuf.*, vol. 23, p. 1005, 2024. https://doi.org/10.30919/esmm1005

[5] S. Mahajan, H. Yadav, and S. Rellegadla, "Polymers for enhanced oil recovery: Fundamentals and selection criteria revisited," *Appl. Microbiol. Biotechnol.*, vol. 105, pp. 8073–8090, 2021. https://doi.org/10.1007/s00253-021-11618-y

[6] S. Chernyshov, V. Repina, N. Krysin, and D. I. M. MacDonald, "Improving the efficiency of terrigenous oil–saturated reservoir development by the system of oriented selective slotted channels," *J. Min. Inst.*, vol. 246, pp. 660–666, 2020. https://doi.org/10.31897/PMI.2020.6.8

[7] R. Zhang, L. Wang, J. Li, C. Feng, and Y. Zhang, "Numerical analysis of perforation during hydraulic fracture initiation based on continuous–discontinuous element method," *Comput. Model. Eng. Sci.*, vol. 140, no. 2, pp. 2103–2129, 2024. https://doi.org/10.32604/cmes.2024.049885

[8] S. Chernyshov, S. Popov, S. Varushkin, A. Melekhin, S. Krivoshchekov, and R. Shaoran, "Scientific justification of the perforation methods for famennian deposits in the southeast of the perm region based on geomechanical modeling," *J. Min. Inst.*, vol. 257, pp. 732–743, 2022. https://doi.org/10.31897/PMI.2022.51

[9] S. Nurov, R. Yakupov, S. Mukhametshin, A. Gareev, L. Kuleshova, and I. Faizov, "Increasing the efficiency of the management of carbonate oil deposits development in the kashiro-podolsk deposits of the birsk saddle," *SOCAR Proc.*, no. 1, pp. 090–098, 2022. https://doi.org/10.5510/OGP2022SI100650

[10] M. M. Huque, S. Imtiaz, and A. Rahman, "Kick detection and remedial action in managed pressure drilling: A review," *SN Appl. Sci.*, vol. 2, p. 1178, 2020. https://doi.org/10.1007/s42452-020-2962-2

[11] G. Doskazieva and G. Imangalieva, "Increasing the permeability of the bottomhole formation zone using chemical reagents," *Eurasian Union Sci.*, vol. 10, no. 6, pp. 22–25, 2020. https://doi.org/10.31618/ESU.24139335.2020.6.79.1073

[12] K. Patel, S. Manan, and A. Sircar, "Plasma pulse technology: An uprising eor technique," *Pet. Res.*, vol. 3, no. 2, pp. 180–188, 2018. https://doi.org/10.1016/j.ptlrs.2018.05.001

[13] S. Thomas, "Enhanced oil recovery – An overview," *Oil Gas Sci. Technol.*, vol. 63, no. 1, pp. 9–19, 2008, accessed on Oct. 27, 2025. https://hal.science/hal-02001980/document

[14] D. Shaikhah, V. Loise, R. Angelico, M. Porto, P. Calandra, A. Abe, F. Testa, C. Bartucca, C. Oliviero Rossi, and P. Caputo, "New trends in biosurfactants: From renewable origin to green enhanced oil recovery applications," *Molecules*, vol. 29, no. 2, p. 301, 2024. https://doi.org/10.3390/molecules29020301

[15] M. Adeel, A. Hassan, H. Sher, and A. Murtaza, "A grade point average assessment of analytical and numerical methods for parameter extraction of a practical pv device," *Renew. Sustain. Energy Rev.*, vol. 142, p. 110826, 2021. https://doi.org/10.1016/j.rser.2021.110826

[16] J. Yang, H. Liu, and W. Xu, "A simulation study of hydraulic fracturing design in carbonate reservoirs: a middle east oilfield case study," *J. Pet. Explor. Prod. Technol.*, vol. 13, pp. 1107–1122, 2023. https://doi.org/10.1007/s13202-022-01577-z

[17] J. Guo, B. Ning, H. Yan, C. Jia, and Y. Li, "Production performance analysis for deviated wells in carbonate gas reservoirs with multiple heterogeneous layers," *Front. Energy Res.*, vol. 10, p. 861780, 2022. https://doi.org/10.3389/fenrg.2022.861780

[18] V. Kuleshov, V. Pavlov, A. Levanov, and N. Ignatjev, "Conducting hydraulic fracturing at a low-temperature carbonate facility," *Oil Gas Expo.*, no. 6, pp. 39–46, 2023, accessed on Oct. 27, 2025. https://www.runeft.ru/upload/iblock/016/24u8u7ek09ew128pmvo003yod32ghfvf.pdf

[19] S. S. Hamdi, H. H. Al-Kayiem, and M. S. Alsabah, "A comparative study of dispersed and grafted nanofluids of graphene nanoplatelets with natural polymer in high salinity brine for enhanced oil recovery," *J. Pet. Sci. Eng.*, vol. 210, p. 110004, 2022. https://doi.org/10.1016/j.petrol.2021.110004

[20] B. Jia, J. S. Tsau, and R. Barati, "A review of the current progress of CO_2 injection EOR and carbon storage in shale oil reservoirs," *Fuel*, vol. 236, pp. 404–427, 2019. https://doi.org/10.1016/j.fuel.2018.08.103

[21] M. Hafez, A. Ratanpara, Y. Martiniere, M. Dagois, and M. Ghazvini, "CO_2-monoethanolamine-induced oil swelling and viscosity reduction for enhanced oil recovery," *J. Pet. Sci. Eng.*, vol. 206, p. 109022, 2021. https://doi.org/10.1016/j.petrol.2021.109022

[22] M. M. M. Alam, A. Hassan, M. Mahmoud, N. Sibaweihi, and S. Patil, "Dual benefits of enhanced oil recovery and CO_2 sequestration: The impact of CO_2 injection approach on oil ecovery," *Front. Energy Res.*, vol. 10, p. 877212, 2022. https://doi.org/10.3389/fenrg.2022.877212

[23] P. Zhang, M. Xu, R. Zhang, X.-C. Ye, J. Qiu, M.-J. Wei, and Y.-R. Li, "Study and application on highly effective development technology in low permeability and tight gas reservoirs," in *Proceedings of the 2022 International Petroleum and Petrochemical Technology Conference*, 2023, pp. 60–72. https://doi.org/10.1007/978-981-99-2649-7_6

[24] D. A. Al-Obaidi and B. I. Ahmed, "Optimization of horizontal well location and completion to improve oil recovery for an Iraqi field," *Iraqi Geol. J.*, vol. 56, no. 2F, pp. 228–245, 2023. https://doi.org/10.46717/igj.56.2F.15ms-2023-12-21

[25] H. Tang, P. H. Winterfeld, Y.-S. Wu, Z. Huang, Y. Di, Z. Pan, and J. Zhang, "Integrated simulation of multistage hydraulic fracturing in unconventional reservoirs," *J. Nat. Gas Sci. Eng.*, vol. 36, no. A, pp. 875–892, 2016. https://doi.org/10.1016/j.jngse.2016.11.018

[26] J. Wu, B. Zeng, L. Chen, H. Huang, and Y. Guo, "Numerical simulation of hydraulic fracture propagation after thermal shock in shale reservoir," *J. Pet. Explor. Prod. Technol.*, vol. 14, pp. 997–1015, 2024. https://doi.org/10.1007/s13202-023-01744-w

[27] X. Gong, Z. Jin, X. Ma, and Y. Liu, "Numerical simulation of the effect of shale lamination structure on hydraulic fracture propagation behavior," *Geomech. Geophys. Geo-Energy Geo-Resour.*, vol. 11, no. 51, 2025. https://doi.org/10.1007/s40948-025-00968-w

[28] Z.-F. Luo, J.-B. Li, N.-L. Zhang, and X.-Q. Zeng, "Numerical study of the mechanism of fracture height extension in shale reservoirs," in *Proceedings of the International Field Exploration and Development (IFEDC2023)*, Singapore, 2024, pp. 1–12. https://doi.org/10.1007/978-981-97-0260-2_3

[29] H. Cao, M. Liao, Y. Lv, and P. Sun, "An integrated insight into the effect of discrete fracture network on hydraulic fracture extension: Numeral simulation investigation," *Acta Geophys.*, vol. 73, pp. 3307–3321, 2025. https://doi.org/10.1007/s11600-025-01556-y

[30] A. Ahmadi, S. Alizadeh, D. Tananykhin, S. Hadi, P. Iliushin, and A. Lekomtsev, "Laboratory evaluation of hybrid chemical-enhanced oil recovery methods coupled with carbon dioxide," *Energy Rep.*, vol. 7, pp. 960–967, 2021. https://doi.org/10.1016/j.egyr.2021.02.005

[31] T. Khaliullin, "Opportunities of digital technologies in enhanced oil recovery," *Int. Sci. Res. J.*, vol. 3, no. 141, 2024.

https://doi.org/10.23670/IRJ.2024.141.1
[32] V. Duplyakov, A. Morozov, D. Popkov, E. Shel, A. Vainshtein, E. Burnaev, A. Osiptsov, and G. Paderin, "Data-driven model for hydraulic fracturing design optimization. Part II: Inverse problem," *J. Pet. Sci. Eng.*, vol. 208, p. 109303, 2022. https://doi.org/10.1016/j.petrol.2021.109303
[33] A. Dmitrievsky, N. Eremin, and V. Stolyarov, "Current issues and indicators of digital transformation of oil and gas production at the final stage of field operation," *SOCAR Proc.*, no. 2, pp. 1–13, 2021. https://doi.org/10.5510/OGP2021SI200543
[34] N. Barros-Galvis, F. Samaniego, and H. Cinco-Ley, "Fluid dynamics in naturally fractured tectonic reservoirs," *J. Pet. Explor. Prod. Technol.*, vol. 8, pp. 1–16, 2018. https://doi.org/10.1007/s13202-017-0320-8
[35] H. Al-Kayiem and I. Jamil, "Fundamental investigation of the oil/water flow emulsion in the downhole by CFD simulation," *WIT Trans. Ecol. Environ.*, vol. 224, no. 11, pp. 541–551, 2017. https://doi.org/10.2495/ESUS170501
[36] I. Jamil and H. Al-Kayiem, "Simulation analysis of the oil/water structure in the downhole with presence of a hydrocyclone separator," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 100, p. 012025, 2015. https://doi.org/10.1088/1757-899X/100/1/012025
[37] I. Les, "Device for hydraulic fracturing of a formation," Patent, accessed on Oct. 27, 2025. https://www1.fips.ru/registers-doc-view/fips_servlet?DB=RUPATAP&DocNumber=2022122568&TypeFile=html
[38] S. S. Hamdi, H. H. Al-Kayiem, and A. S. Muhsan, "Natural polymer non-covalently grafted graphene nanoplatelets for improved oil recovery process: A micromodel evaluation," *J. Mol. Liq.*, vol. 310, p. 113076, 2020. https://doi.org/10.1016/j.molliq.2020.113076
[39] H. H. Al-Kayiem and J. A. Khan, "Evaluation of Alkali/Surfactant/Polymer flooding on separation and stabilization of water/oil emulsion by statistical modeling," *Energy Fuels*, vol. 31, no. 9, pp. 9290–9301, 2017. https://doi.org/10.1021/acs.energyfuels.7b01662
[40] M. K. A. Khan, J. A. Khan, H. Ullah, and H. H. Al-Kayiem, "De-emulsification and gravity separation of micro-emulsion produced with enhanced oil recovery chemicals flooding," *Energies*, vol. 14, no. 8, p. 2249, 2021. https://doi.org/10.3390/en14082249
[41] W. Aleem, N. Mellon, A. J. Khan, and H. H. Al-Kayiem, "Experimental investigation and mathematical modeling of oil/water emulsion separation effectiveness containing alkali-surfactant-polymer," *J. Dispersion Sci. Technol.*, vol. 42, no. 9, pp. 1286–1298, 2021. https://doi.org/10.1080/01932691.2020.1738244
[42] S. Sokhoshko and S. Madani, "Features of gas inflow to a horizontal wellbore at various trajectories," *Oil Gas Stud.*, no. 6, pp. 90–102, 2021. https://doi.org/10.31660/0445-0108-2021-6-90-102

Nomenclature

$\dot{m}$	mass flow rate, kg/m^3
T	temperature in Kelvin or °C

Abbreviations

EOR	enhanced oil recovery
BFZ	Bottom-Flow Zone
CFD	computational fluid dynamics
CO_2	carbon dioxide
JSC	Joint Stock Company
LLC	Limited Liability Company
MGRP	Massive Gravity-Assisted Recoverable Pressure
MSHF	technologies continue to improve
NWZ	Near-Wellbore Zone
NC	National Company
NNK	Naftogaz Holding National Corporation
pcs	number of perforations
RIW	Radial Inflow Well
SAGD	Steam Assisted Gravity Drainage
TPS	Tunnel Perforation System