






Review

A Technology of Hydrocarbon Fluid Production Intensification by Productive Stratum Drainage Zone Reaming

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Abstract: The paper proposes a new technology for fluid production intensification, in particular hydrocarbons, which is implemented via significant increasing of the local wellbore diameter in the interval, where the productive stratum is present. The proposed technology improves the well productivity by increasing the filtration surface area and opening new channels for filtering fluids into the well. The innovative, technical idea is to drill large diameter circular recesses in planes perpendicular to the well axis. After that, the rock mass located between the circular recesses are destroyed by applying static or dynamic axial loads. The required value of the axial force is provided by the weight of the standard drilling tool. As a result of the study, the analytical relations to specify the admissible radius of circular recesses and admissible thickness of rock mass between two adjacent circular recesses from the condition of safe operation are obtained. The numerical analysis carried out for typical reservoir rocks substantiated the possibility of well diameter local reaming twenty times. A special tool for circular recess drilling is developed and the principle of its operation is described. The advantage of the proposed approaches is the low energy consumption for well diameter reaming. Our technology will have special economic expediency for the intensification of production from hydrodynamically imperfect wells and under the condition of fluid filtration according to the expressed nonlinear law.

Keywords: well reamer; rock mass; intensification of production; nonlinear law; completion of wells; innovative technology



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1. Introduction

Today, the current problem of the energy industry is development of classical and new technologies (including environmentally attractive and energy-saving mining ones) to increase well productivity for oil/gas drilling [1,2]. New technological schemes for coal reserves working out with gasification are developing, which will additionally allow non-commercial and abandoned mine reserves to be used and the mining enterprises duration to be extended [3,4]. In general, the country's energy sector is the basis of the economy and industry, because any production requires energy resources [5–7]. Our study is involved in solving this problem.

A well flow rate increases if the well diameter increases for the interval of the productive stratum, the depression of the stratum decreases, as well as the pressure gradient of the well wall, and the drainage zone expands. Note that we are not talking about the

classic reamer applications to increase wellbore but about increasing the diameter of the well more than five times in a clearly defined interval. It is possible to increase the diameter of the wellbore in the interval of the productive stratum at the end of well development immediately after drilling or during the overhaul of existing production or injection wells. Sometimes, liquid and gas extraction from the productive stratum is limited by the requirement not to exceed a certain value of the filtration rate, at which the intensive removal of sand into the well begins. If the production is limited by the abovementioned geological factor, the maximum allowable flow rate of the well is directly proportional to the radius of its bottomhole.

Based on the analysis of radial and spherical inflows of linear or nonlinear fluids to the well, the following conclusion was made.

The greater effect of well diameter change on the flow rate is associated with the more significant well deviation from the hydrodynamic perfection of its completion and the more expressed nonlinearity of the fluid filtration law. This is especially expressed at a significant flow rate of the well when there is a crisis of the linear law of filtration in the bottomhole zone. In this case, the predicted increase in the well flow rate can reach the value of $n^{2/3}$, where n —the multiplicity of the well diameter—increases [8–10].

The works [11,12] have carried out a thorough analysis of the expected effects of the well diameter increasing in the productive stratum interval. In particular, this makes it possible to solve the following tasks: the colmatted layer removal in the bottomhole zone to reduce the resistance of fluid inflow into the well; completion of existing and creation of new filtration channels especially typical for limestone collectors; and prevention of sand separation by reducing depression on the stratum and creating quality gravel filters.

Therefore, a significant increase of the well diameter in the productive stratum can provide a significant increase of well productivity. Thus, development of a technology for the significant increasing of the wellbore diameter of the productive stratum interval is an issue at stake for the oil and gas industry. This technology should be technically simple and implemented at a reasonable financial cost. The urgency of the task and the expected profitability of the results of its solution became the main motivators of our study.

To date, a number of devices have been designed to expand the diameter of the well in a certain interval. Usually, drilling tools operate in aggressive and abrasive environments under the action of intense loads, so their performance is subject to special requirements [13,14]. This issue is especially significant for tools used for difficult technological operations. In particular, a number of methods are applied to improve the performance of high-tech drilling tools. Design methods envisage drill pipe design modification [15], threaded joint improving [16–18], ensuring the accuracy of threads [19] and preventing their self-unscrewing [20], parametric optimization of cutters, supports and washing units of rock-destroying tools [21,22], etc. Among the technological methods are the rational reinforcement of steel parts [23], optimization of the formation of helical surfaces and surfaces of complex topology [24], and application of flexible [25,26] and functionally gradient [27–30] coatings. Operational methods to increase drilling tool performance include substantiation of drilling modes taking into account the force [31,32] and temperature interactions [33], ensuring thorough flushing of the bottomhole [34], and usage of vibration protection for drill strings [35,36]. Researchers pay special attention to effective ways to eliminate complications during drilling and improve well completion technologies [37,38]. The design features of drilling tools, specifics of operation conditions and contact interaction with the well cause vibrations and dynamic loads. General approaches to contact analysis of pipes and drilling tools with an elastic medium are presented in [39,40]. The most radical way to solve the problem of tool vibration protection is based on the use of special vibration protection devices: elastic couplings, drill shock absorbers and elastic spindles of downhole motors [41], and dynamic extinguishers and specialized dampers [42].

In general, modern equipment to ream well diameter can be categorized by design into two groups. The first group includes reamers with fixed PDC cutters [43] and reamers

with retractable cutters [44,45], which are not able to increase the well diameter more than twice. Such devices are mainly used to remove the colmatted layer from the walls of the well, align the wellbore, increase the drilling speed of large diameter wells, etc. These tools are actively used for both marine and earth drilling, but their designs do not allow well diameter to be significantly reamed and this can significantly affect the flow rate.

The second group includes devices to ream the well diameter more than twice. Among the mechanical devices, this group include reamers with deflecting PDC cutters and reamers with deflecting cones on the legs [46,47]. Hypothetically, such devices can ream the well diameter several times for several paths. Non-mechanical ways to expand the wellbore for significant increasing of the well diameter include erosion of the rock using a rotary hydro-sandblasting head [48] or erosion of the rock by circulating fluid outside the casing [49]. A geomechanical model of rock mass, the behavior of which depends on the mining and geological conditions and mining parameters of the hydrocarbon production process, is presented in [50–52]. In studies [53,54] the experimental study of the thermal reaming of the borehole via axial plasmatron are discussed. Although the considered methods allow the well diameter to be significantly reamed, their application is associated with high energy consumption and low productivity for cases when it is necessary to increase the well diameter more than five times. In our opinion, the main gap in the known research is the inefficient use of axial force to implement the process of well diameter local reaming. The disadvantage of the considered non-mechanical methods of well reaming is the entire rock mass is destroyed by the directed flow. Accordingly, the application of such methods requires significant energy and time, and their efficiency depends on the mechanical properties of the rock and decreases nonlinearly with the increasing diameter of the recess. Devices for mechanical reaming of the well diameter destroy the rock mass via cutting and require a significant torque. It should be noted that the bottomhole assembly limits the value of torque that can be applied to the tool. Therefore, obtaining recesses of a large diameter is possible only when drilling in several passes. The drill string has a lot of weight and we are able to create a large axial load without any technical difficulties. In view of this, the idea arose to develop an approach that would allow the effective use of axial force to destroy rocks in the process of local reaming of the well diameter.

This study aims to develop technological and technical support for local increasing of well diameter (more than five times) in the productive stratum interval. To achieve this goal, the following tasks were set:

- specification of ideas and hypotheses of the study;
- development of formation stages of the expanded drainage zone of a productive stratum;
- specification of admissible dimensions of circular recesses and interval of their drilling from conditions of safety operation;
- testing the possibility of the proposed technology application based on the condition of strength of the formed reservoir rock mass; and
- development of the technical mean design to implement the technology of well diameter local reaming.

2. Materials and Methods

At the first stage of the research, we used the bibliosemantic method and content analysis to deeply study the problem and choose an effective way to solve it. The analysis of previous research based on scientific literature sources, electronic resources, as well as practical and production experience of the authors made it possible to select the necessary scientific data according to a certain logic, classify them, and specify relations links and relationships between them. As a result, the purpose and objectives of the study were formulated.

The main ideas and concepts of the innovative technology for well diameter reaming in the area of productive stratum were formulated in order to increase its flow rate using the methods of structural-logical and system analysis. It was determined that the well reaming process should be carried out in several stages, and well diameter increasing

should be significant (more than five times) and carried out in a clearly defined interval of the well. The process of the technology development was organized to provide the main volume of the rock collapsing only under the influence of axial force, the magnitude of which is provided by the weight of the drilling tool.

Based on the methods of mechanics of deformable solids, the problem of the limit equilibrium of the rock mass formed by two circular recesses was formulated and solved. An analytical method for solving this problem has been developed to determine the stress state and evaluate the strength of the considered system. The reliability of the obtained results was confirmed via the validity of the geometric-linear formulation of the problem, strict implementations of mathematical methods tested in the literature for analytical research, and convergence of the results of partial (limit) cases with known results. In general, the possibility of applying the proposed technology for typical reservoir rocks is substantiated.

For numerical approbation of the results, some typical rocks were chosen: siltstone, sandstone, fine-grained limestone, and dolomite.

Next, we applied the so-called method of the basic unit (basic design). The method is based on the usage of a basic structure to be transformed into a machine for the desired purpose by attaching special equipment. The basic unit is a drilling tool, which is produced in series. Therefore, using the method of the basic unit (basic design), as well as the sequential compounding method, a special tool and special configurations of the drill string were developed for the practical implementation of the proposed technology.

Let us formulate the basic concepts of a new method of well diameter significant reaming in the area of productive stratum to increase the flow rate of the well. Well diameter reaming envisages several stages, which are schematically shown in Figure 1.

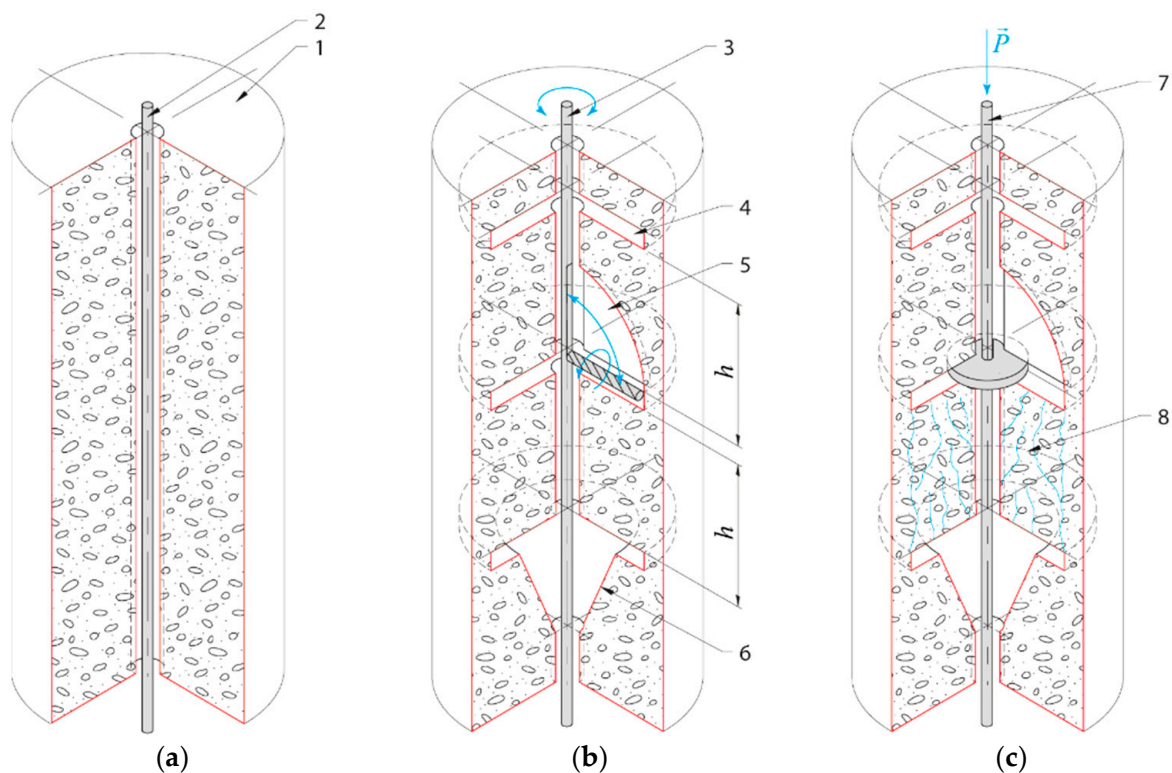


Figure 1. Stages of productive stratum expanded drainage zone formation: 1—rock, 2—drill string, 3—special bottomhole assembly for radial hole drilling in the well, 4—circular recess, 5—recess formed by drilling of the radial hole, 6—conical hole, 7—special bottomhole assembly for cantilever rock destruction and grinding, 8—zone of rock destruction by static and dynamic axial force.

The first stage is drilling of the well with the nominal radius of r in the productive stratum (Figure 1a). After that, a special bottomhole assembly is lowered into the well with a device with a bit that can be deflected. This bit drills a deep circular recess with the radius of R in the wellbore interval to be reamed with the predetermined step of h . The recess that is furthest from the bottomhole is drilled in the form of a cone (Figure 1b). Next, the bottomhole assembly with a jar or other device that can create a variable axial load and a device with retractable legs is lowered into the well. This assembly applies static and dynamic axial force to rock mass formed by two circular recesses. As a result, the rock mass is destroyed, crushed, and removed by washing liquid to the surface (Figure 1c).

3. Results

3.1. Specification of Circular Recess Allowable Dimensions and Interval of Its Drilling

The proposed technology envisaged that the rock mass between circular recesses should remain intact at the second stage of the operation (Figure 1b) and be guaranteed to be destroyed when applying axial force, which is technologically possible to apply at the third stage of the process (Figure 1c).

The allowable size of circular recesses and the interval of their drilling h (see Figure 1b) are specified by the strength of the rock mass between two adjacent recesses. We assume intuitively the following: too small a specified drilling interval or a too big radius of circular recesses can lead to premature destruction of the rock mass and an emergency situation (clamping the deviated bit by the rock mass). In addition, if the drilling interval is specified too big, the maximum applicable axial force P may not be sufficient to destroy the rock mass.

To find out whether we are right in the declared assumptions, let us consider the following problem.

Let us consider the rock mass in the form of a round plate with the thickness of h and the outer radius of R having a technological slot and a through hole with the radius of r (Figure 2). The plate is loaded with bulk forces, the intensity of which is determined by the specific weight of the rock, and the plate can be additionally loaded with axial force P .

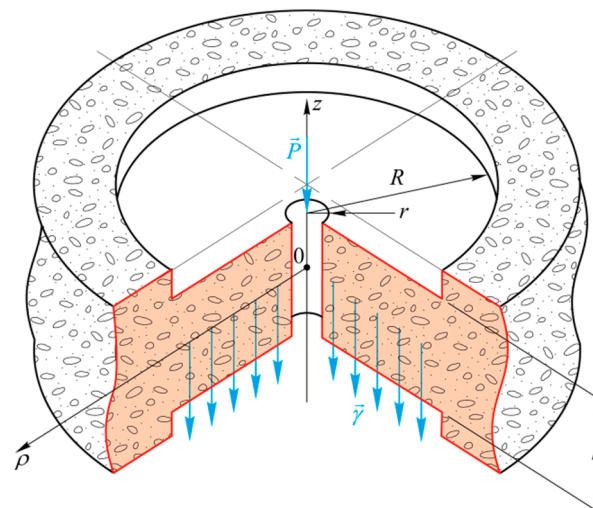


Figure 2. Calculation scheme of the rock mass.

The proposed technology assumes that the plate is thick. As the thick plate is not very susceptible to bending, we will take into account the shear of the rock when assessing the strength. Let us consider the limit equilibrium of the plate (Figure 2):

$$\int_s \tau ds - \int_V \gamma dV - P = 0 \quad (1)$$

After the transformations we obtain a relation for the tangential stress averaged over the thickness of the plate:

$$\tau = \frac{1}{2} \left(\frac{P}{\pi \rho h} + \gamma \rho \left[1 - \left(\frac{r}{\rho} \right)^2 \right] \right), \rho \in [r, R], \quad (2)$$

where s is the area of the plate side surface of radius ρ and V is the volume of the plate.

Analysis of relation (1) indicates that large values of P near the through hole may have a boundary effect (the case when the tangential stresses in the hole are greater than the stresses in the clamping zone of the plate). We assume that the technical means of plate loading (a device with retractable legs) will eliminate the manifestation of this effect. Therefore, we neglect the influence of the described boundary effect and assume $\rho = R$ in expression (1) and obtain the rock mass strength condition:

$$\tau_{\max} = \frac{1}{2} \left(\frac{P}{\pi R h} + \gamma R \left[1 - \left(\frac{r}{R} \right)^2 \right] \right) \leq \tau_u, \quad (3)$$

where τ_u is the maximum resistance to rock displacement (determined by the strength passport of a particular rock).

Analysis of relation (2) shows that the boundary state of the plate loaded by bulk forces depends on the plate radius and the specific gravity of the reservoir rock. Therefore, in order to provide integrity of the plate formed by two adjacent circular recesses within drilling, it is necessary to meet the following conditions:

$$\frac{1}{2} \gamma R \left[1 - \left(\frac{r}{R} \right)^2 \right] \leq \frac{\tau_u}{\zeta k'}, \quad (4)$$

where ζ is the coefficient of operational conditions (depends on the coefficient of water saturation of the rock, the coefficient of porosity, thermal impact, etc.) and k is the coefficient of strength.

The thickness of the rock mass h_{\max} between the circular recesses should be specified from the condition of its possible destruction under the applied axial force. Therefore, the maximum thickness of the rock mass h_{\max} to be destroyed by the applied axial force P is specified by the formula:

$$\frac{1}{2} \gamma R \left[1 - \left(\frac{r}{R} \right)^2 \right] \leq \frac{\tau_u}{\zeta k'}, \quad (5)$$

where λ is the coefficient of axial force application dynamism (for static application of axial force $\lambda = 1$, for sudden application). If there is a necessity for percussion mechanisms or application of deep vibrators, the coefficient of dynamism can be determined using the methods presented in [55–57].

3.2. Specification of Circular Recess Allowable Dimensions and Interval of Its Drilling

The possibility of applying the proposed method of wellbore reaming is limited by the strength of the cantilever rocks and the possibility of their further destruction. To do this, we numerically estimated several typical types of reservoirs. Hydrocarbon collectors are rocks with pores, cavities, or systems of cracks and are able to retain and filter fluids (oil, gas, etc.). The vast majority of reservoir rocks are of sedimentary origin, but in practice, there is often a combination of different types of reservoirs with a predominance of one or another type. Four typical reservoir rocks were selected for the study; Table 1 presents their characteristics [58].

We assume that the rock mass with the following characteristics is formed as a result of drilling: $r = 0.2 \text{ m}$, $\zeta = 0.2$, $k = 1.5$.

According to (3) we obtain the maximum stresses, τ_{\max} , in the reservoir rocks referring to the radius of the circular recesses (Figure 3). Assuming that the maximum stresses, $\tau_{\max i}$, for the selected rock are equal to the allowable stresses, $[\tau]_i$, we determine the allowable

radius of the circular recesses $[R]_i$. For the selected rocks, the allowable radius of the recesses are as follows: siltstone $[R]_1 = 2.82$ m, sandstone $[R]_2 = 3.1$ m, fine-grained limestone $[R]_3 = 3.46$ m, and dolomite $[R]_4 = 2.18$ m.

Table 1. Characteristics of reservoir rocks.

Reservoir Rock	Siltstone	Sandstone	Limestone Fine-Grained	Dolomite
Index i	1	2	3	4
Specific weight of the rock, N/m^3	1.95×10^4	2.4×10^4	2.71×10^4	2.94×10^4
Maximum shear resistance, KPa	82	110	140	95
Allowable stresses, $[\tau]_i = \tau_{ui} / \zeta_i k_i$, KPa	54.7	73.3	93.3	63.3

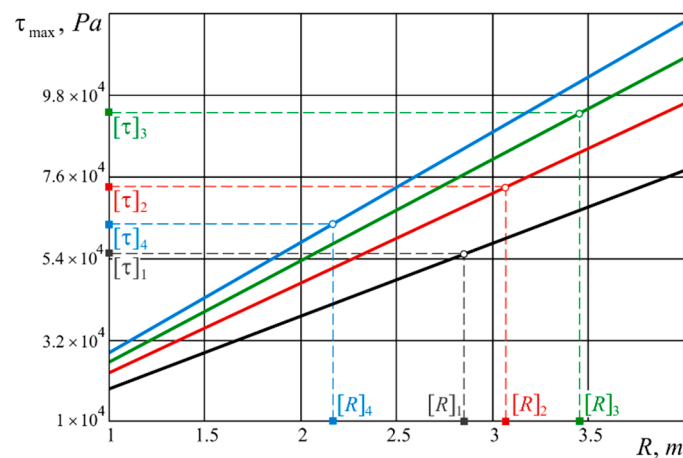


Figure 3. Determination of allowable drilling radii of circular recesses from the condition of rock mass strength: 1—siltstone, 2—sandstone, 3—fine-grained limestone, 4—dolomite.

Due to design and technological limitations of the device for circular recesses drilling, their radius does not exceed 2.5 m ($R \leq 2.5$ m). Therefore, the obtained results show that based on the technical capabilities of recess drilling, the condition of strength of the cantilever rock mass is met for most reservoir rocks.

To determine the maximum allowable thickness of the rock mass, which can be formed between two adjacent circular recesses, we use formula (4). Axial static loading of 1000 kN was statically applied to the formed rock mass by heavy weight drill pipes. Figure 4 shows the allowable thickness of the rock mass referring to the circular recess radius (abscissas of the curve break corresponds to the values of $[R]_i$). It is observed that the radius of the rock mass (if other conditions are constant) leads to a rapid decrease in the allowable thickness of the rock mass only at a certain interval. Outside this interval, the rate of decline of the allowable thickness decreases, stabilizes, and then stops altogether. The reliability of the obtained results is confirmed by the validity of the problem statement and the strict implementation of the mechanical and mathematical methods tested in the literature for analytical research [25,42].

In practice, the thickness h of the rock mass should be slightly less than the calculated value h_{\max} to ensure guaranteed destruction of the rock and to neutralize the error of the bottomhole assembly position in the well. Under certain conditions, a certain step of drilling circular recesses h at their radius of $R = 1.7$ – 2.5 m makes it difficult to implement the proposed technology using only static axial force (for example, reservoir rock and $i = 3$ in Figure 4). Note that h_{\max} linearly depends on the coefficient of dynamism λ . Therefore, if necessary, h_{\max} can be adjusted to a larger range to provide rock mass destruction by applying a dynamic axial load.

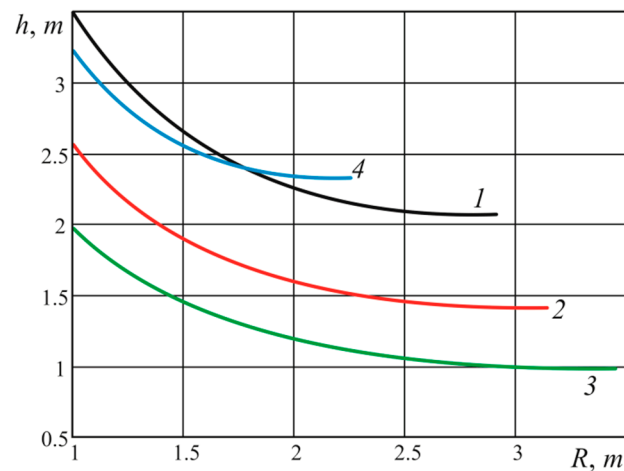


Figure 4. Determination of the circular recess drilling interval: 1—siltstone, 2—stone sandstone, 3—fine-grained limestone, 4—dolomite.

3.3. Technical Means for Local Reaming of the Well Diameter

To explain the technology of wellbore reaming, let us consider the schematic diagrams of special drilling equipment and describe the principle of its operation. Figure 5 schematically shows the special bottomhole assembly (BHA) used at the second and third stages of wellbore diameter reaming.

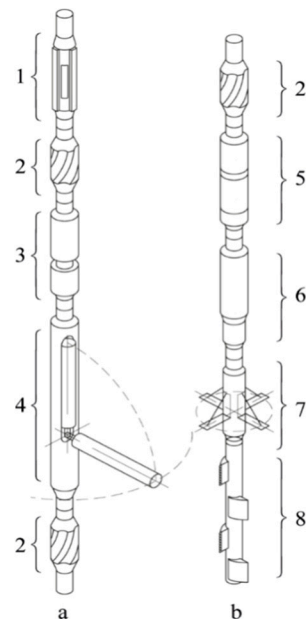


Figure 5. Schemes of bottomhole assemblies: (a) circular and conical recesses drilling and (b) rock mass destruction and grinding; 1—anchor, 2—centralizer, 3—turning gear, 4—special tool with deflecting bit, 5—shock absorber, 6—mechanical vibrogenerator (jar) of longitudinal oscillations, 7—blade raising device, 8—reamer with fixed blades.

The special BHA used for circular recess drilling (Figure 5a) consists of an anchor (1) of known design, designed to fix the drill string relative to the wellbore, two centralizers (2) used to orient the BHA relative to the axis of the well, a rotary device (3) with remote control, and a special device with a rotating bit (4).

The sequence to obtain circular recesses with this BHA is as follows:

- drilling of the well of nominal radius r ;
- the special bottomhole assembly is lowered into the well to a given depth and fixed;

- washing liquid starts circulation, causes the rock-destroying tool rotation, and serves as a trigger for the remote control system on the circular recess drilling to start;
- the remote control system provides a control signal to the linear drive which through the rod (1), via the lever mechanism (2), deflects the rock-destroying tool at an angle of 90 degrees (Figure 6);
- the rotary device (3) rotates the device with the rotary bit around its axis by 360 degrees, and as a result, the circular recess is formed;
- the rock-destroying tool returns to its original position on the signal of the control system, and the BHA is fixed; and
- the BHA rises to a given height h , after which the whole process is repeated.

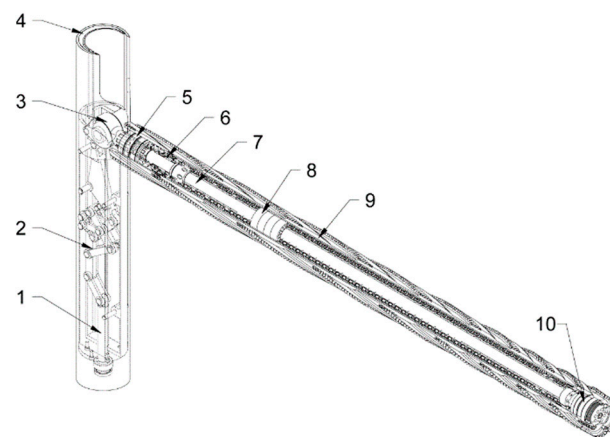


Figure 6. Structural diagram of the special tool with the rotating bit: 1—rod of the linear actuator, 2—lever mechanism, 3—hinge, 4—cavity between the housing and the casing for supplying the flushing fluid, 5—rolling support, 6—reducer, 7—shaft, 8—turbine sections, 9—body—drill bit; 10—rolling support.

After completing the drilling, the tool is removed from the well.

Figure 6 shows the special tool design with the rotating bit. It consists of a hollow bit (see number 10 in Figure 6) with cutters fixed on its surface driven through the gearbox 6 by a section of turbines (8) with movable stators and fixed rotors, or a section of a screw motor with a hollow rotor and torsion bar (not shown) in it. The turbine rotors are attached to the shaft (7) with rolling bearings (5) and (10) at the ends. One end of the shaft (7) is attached to the hinge (3), which can rotate 90 degrees via the lever mechanism (2) due to the movement of the rod of the linear actuator (1). The developed assembly of the special device confirms the possibility of its implementation in the section of the BHA with an overall size of 197 mm and more. Thus, the assembly scheme of the device for the tool with a diameter of 197 mm makes possible usage of the deflecting bit (10) with a diameter of 140–145 mm with the drive in the form of standard sections of turbine drills or sections of a propeller engine with a hollow rotor with a diameter of 85 mm. The maximum length of the bit (10) is determined based on the condition of the strength of the rotary mechanism (2) and the hinge (3), in particular, they should hold the effort to ensure the volumetric destruction of the rock by the bit. Based on the preliminary calculations, the length of the bit is limited to 1.75–2.5 m depending on the bit operation mode, rock mass, and bit cutter characteristics. We used methods to assess the strength and rigidity of long structures, including pipe columns, pipelines, and special tools operation in the conditions of contact interaction with the elastic environment and at operation in difficult geotechnical conditions [59,60].

The BHA (Figure 5b) is lowered into the well after circular recess drilling destroys the rock mass between the circular recesses. It consists of a section of heavy weighted drill pipes which carries out its orientation relative to the axis of the well; one of the known drill shock absorbers (5) [61,62], which protect the drill string from vibration and control the

BHA dynamics [63]; the vibration generator or jar (6); the special device to retract legs (7), which allows independent rotation of the legs around the axis of the BHA; and the section of the eccentric well reamers (6).

The destruction of the rock mass using this bottomhole envisages the following sequence:

- the BHA is lowered into the well, which is positioned in one of the known ways so that the device to retract the legs is in front of the drilled circular recesses;
- the legs retract to the circular recess after the command;
- intensive circulation of the washing liquid begins with simultaneous rotation of the drill string;
- the axial load is applied to the rock mass, the static component of which is created by the weight of the of heavy weighted drill pipes—due to the operation of the vibrator. As a result, the main cracks appear in the rock and its destruction occurs; and
- to prevent trapping of the drill string and high-quality cleaning of the well, pieces of rock that fall into the space between the drill string and the walls of the well are further crushed using the section of eccentric expanders 8 (Figure 3) and are carried to the surface with flushing fluid.

After the destruction of one cantilever rock mass, further destruction of the following is carried out, after which the BHA is removed from the well.

4. Discussion

Well diameter increasing in the interval of the productive stratum leads to an increase in the flow rate of the well, reducing the depression on the stratum and the pressure gradient on the well wall. Increasing the contact area between the bottomhole and the reservoir area (increasing the filtration surface area, opening new channels for filtering fluids into the well, etc.) allows hydrocarbon fluid production to be intensified. It should be emphasized that this is not a classic reaming of the wellbore with traditional reamers, but well diameter increasing more than five times in a clearly defined interval. The greater effect of well diameter change on the flow rate is associated with the more significant well deviation from the hydrodynamic perfection of its completion and the more expressed nonlinearity of the fluid filtration law [8,9]. This is especially expressed at a significant flow rate of the well when there is a crisis of the linear law of filtration in the bottomhole zone. In this case, the predicted increase in the well flow rate can reach the value of $n^{2/3}$ where n —the multiplicity of the well diameter—increases. The procedure of well diameter increasing in the interval of the productive stratum can be carried out immediately after drilling or during the overhaul of existing production or injection wells.

We propose the innovative technology for local well diameter increasing (more than five times) in a clearly defined interval. The peculiarity of the proposed technology is a two-stage process of well reaming. At the first stage, large-diameter circular recesses are drilled in planes that are perpendicular to the well axis. The second stage is the destruction, grinding, and removal to the surface of the rocks located between the drilled circular recesses. Static and dynamic axial forces applied to the special bottomhole assembly are used for rock mass destruction. The sequence of technological operations for wellbore local increasing is presented.

The sequence of technological operations on the local increase in the diameter of the wellbore is presented. The designs of drill string configurations that should be used to implement the proposed technology are proposed:

- layout for drilling disk and conical recesses;
- layout for destruction and crushing of rock mass.
- a special tool with a rotating bit for drilling disk recesses has been developed, its design is presented and the principle of operation is described. The designs of bottomhole assembly for the proposed technology implementation have been presented:
- BHA for circular and conical recess drilling; and
- BHA for rock mass destruction.

A special tool for circular recess drilling and its design are presented, and the principle of its operation is described.

In order to substantiate the possibility of the technology implementation and for determination of its applicability limits, we formulated and obtained a solution to the problem of the limit equilibrium of the rock mass formed between two adjacent circular recesses. We obtained analytical relations to specify the admissible radius of the circular recesses (formula 3) and admissible thickness of the rock mass (formula 4) on the condition of the safe performance of planned technological processes. In general, the possibility of the proposed technology application for typical reservoir rocks is substantiated, in particular for siltstone, sandstone, fine-grained limestone, and dolomite. The carried out analysis showed that the technology can increase the local diameter of the well by twenty times. The tasks of the next stages of our research are field and bench tests of the special tool with the rotating bit and evaluation of the quality of sludge removal when drilling circular recesses of large diameter.

Today, the oil and gas industry are actively developing and improving the classical [64–66] and developing and testing new technologies to increase the productivity of wells [2,67,68]. Each of these technologies has its advantages and disadvantages, as well as economically feasible applications [1,66]. Among all the variety of approaches offered, we try to find our niche. The technology we have developed is technically simple and is implemented at a reasonable financial cost. To destroy the rock mass, our technology effectively uses the axial force provided by the weight of existing drilling tools so the technology is energy efficient. This favourably differs the proposed technology from others aimed at increasing the contact area between the bottomhole and the collector area. Our technology can be used immediately after drilling or in the process of overhauling a well.

5. Conclusions

Analysis of existing studies has shown that under certain geological conditions it is possible to achieve a significant intensification of hydrocarbon production by local reaming of the well diameter in the productive interval. The paper has proposed that the new technology can increase the local well diameter by more than five times in a clearly defined interval. The peculiarity of the proposed technology is a two-stage process of well reaming. At the first stage, large-diameter circular recesses are drilled in planes that are perpendicular to the well axis. The second stage is the destruction, grinding, and removal to the surface of the rocks located between the drilled circular recesses. Static and dynamic axial forces applied to the special bottomhole assembly are used for rock mass destruction.

To test the feasibility of the proposed technology, the authors have considered the problem of rock mass limit equilibrium formed between two adjacent circular recesses. Analytical relations were obtained to specify the admissible radius of the circular recess and admissible thickness of rock mass from the condition of safe operation. Assuming that the maximum stresses for the reservoir rock are equal to the allowable stresses, the maximum allowable values of the radii of the circular recesses were specified. In particular, for the selected reservoir rocks the allowable radius of the circular recess are as follows: 2.82 m for siltstone, 3.1 m for sandstone, 3.46 m for fine-grained limestone, and 2.18 m for dolomite. The thickness of the rock mass between the circular recesses (drilling interval) was specified from the condition of the possibility of rock destruction under the action of axial force. In particular, the maximum allowable drilling interval of circular recesses with a radius of 2 m with a static application of axial force of 100 kN ranges from 1.2 m for fine-grained limestone to 2.3 m for dolomite. The value of the calculated intervals can be adjusted largely in the case of using devices that generate the dynamic component of the axial force during rock mass destruction. In general, the possibility of applying the proposed technological operations for typical reservoir rocks is substantiated.

For the technical implementation of the proposed technology, special bottomhole assemblies have been developed. A special tool to drill circular recesses has also been developed, its design is presented, and the principle of operation is described. The study

showed the possibility of its application for bottomhole assemblies with a radius of 195 mm and more and the possibility of drilling circular recesses with a diameter of up to 2.5 m.

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Nomenclature

h	thickness of the rock mass between two adjacent circular recesses;
R	radius of the circular recess;
r	radius of the through hole in the rock mass;
γ	specific weight of the rock;
P	axial force, which loads the rock mass;
$[R]$	the maximum allowable radius of the circular recess;
ρ	polar coordinate;
s	area of the side surface of the rock mass with the radius of ρ ;
V	volume of rock mass;
τ	tangential stresses in the rock mass;
τ_{\max}	maximum tangential stresses in the rock mass;
τ_u	ultimate resistance to rock displacement;
ζ	coefficient of operational conditions (depends on water saturation of the rock, the porosity coefficient, thermal impact);
k	safety factor;
λ	the coefficient of axial force application dynamics.

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