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PREDICTION OF HYDRAULIC FRACTURING PARAMETERS IN TERRIGENOUS RESERVOIRS AT RAKYTNYANSKE GAS FIELD WITH REGARD TO GEOMECHANICAL PROPERTIES OF ROCKS

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The object of this study is the process of fracture formation in the terrigenous reservoirs at the Rakytnyanske gas field, located in Ukraine in the Kharkiv oblast. The formation of fractures in the productive horizon has been investigated by designing hydraulic fracturing (HF), which is used to stimulate fluid inflow under the conditions of well No. 4. This method involves the use of innovative hydraulic fracturing fluids, which allows for the optimal geometry of the fractured formation, its sufficient conductivity and, ultimately, an increase in the well productivity.

Hydraulic fracturing is one of the most effective methods for improving well production, especially in low-permeability and complex formations. This technology is widely used in the oil and gas industry to develop both conventional and unconventional reservoirs. By creating a system of fractures in the reservoir, hydraulic fracturing makes it possible:

– to improve the permeability in the formation zone around the reservoir;

– to increase the area of fluid filtration through the formation to the well;

– to change the direction of fluid flow in the formation.

The basic hydraulic fracturing operation performed has resulted in a fracture with a half-length of 136.9 m, a total fracture height of 36.5 m, and a width of 0.0 mm to 3.7 mm with an average value of 1.5 mm. Thus, the crack was longer than designed under reduced profile geometry parameters. The crack formed at a high average wellhead pressure of 560 kgf/cm². During the basic hydraulic fracturing process, 120 m³ of fluid and 23.9 tons of propane were injected, thereby achieving an average concentration of 2.57 kg/m², which created conditions for the preservation of the main fracture and channels, their consolidation, as well as enabled good permeability.

The simulation results obtained using FracCADE software were successfully applied to the Rakytnyanske gas field development project in the Kharkiv oblast. By optimizing the hydraulic fracturing process in complex geological structures, it was possible to increase well production rates by more than 35 times and reduce costs

Keywords: hydraulic fracturing, FracCADE, fracture conductivity, fracture geometry, terrigenous reservoir

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1. Introduction

As the driving force of the economy, the oil and gas industry is constantly looking for new ways to increase production. This is achieved through the introduction of innovative technologies at existing wells, the development of new deposits, and the active exploration of marine resources.

The least expensive way is to increase production (intensification) of hydrocarbons at wells that are in operation. But the issue related to complete production of already discovered reserves of hydrocarbon raw materials is that many deposits are at the final stage of development. The application of one or another intensification method could prove impractical, inefficient, or not effective at all [1]. In order to achieve a positive result in such fields, it is necessary to deeply analyze the condition of the wells, the remaining reserves, the filtration capacity properties of the rock-reservoirs, the characteristics of the deposits, and their mode of operation [2]. The main task of activities in this area should be the involvement in the development of mining reserves, which are located in reservoirs with high lithological heterogeneity, both in terms of area and thickness of productive sections. Particular attention is paid to reservoirs with low filtration properties or those that have deteriorated due to one or another condition during deposit development [3].

The majority of all worldwide reserves of hydrocarbons, both conventional and hard-to-extract, are contained in terrigenous reservoirs. Therefore, this type of reservoir comes to the fore as the main one for conducting research and applying modern technologies and equipment.

Hydraulic fracturing is one of the main and most effective methods for increasing the productivity of wells. Studying the regularity of the formation and propagation of cracks is decisive for this process, the purpose of which is primarily to obtain the optimal design of the crack and the best possible conductivity. This, in turn, creates conditions for increased hydrocarbon production.

Research into devising the optimal design of hydraulic fracturing followed by its implementation in production is very relevant; in the end, it makes it possible to achieve a significant economic effect in a short period of time due to the increase in the profitability of production.

2. Literature review and problem statement

Paper [1] provides brief information about the conducted experiments for laboratory modeling, the materials used in hydraulic fracturing, as well as a comparison of rock fracture pressures under different experimental conditions. In addition, the behavior of various rocks during the propagation of cracks under the influence of various factors has been carefully studied [2]. The results of experiments are systematically differentiated and integrated to investigate the influence of various factors on crack propagation. The initiation of hydraulic fracturing is fully characterized by three parameters, namely initiation pressure, initiation orientation, and initiation length. The strength-based criterion covers only two of these parameters, pitting pressure, and orientation. Unsolved issues with length estimation remain, because it requires a mixed critical approach, in which both stress and energy conditions are fulfilled [3, 4].

In experiments [5], it was established that material anisotropy can reduce stress anisotropy in the sense that it can direct the crack to the weakest plane. From the point of view of fracture energy, it is shown that the initiation length cannot be as large as the length of the fracture process zone, even if the size of the wellbore is unrealistically large. The difference between the initial pressures predicted by the mixed criterion and the strength-based theory increases as the size of the wellbore decreases. Based on these observations, the question of applying the mixed criterion remains unresolved, especially in relatively small wellbores. Therefore, various types of software are used to simulate this process. Work [6] shows the innovative approach "AE-ATT-ConvLSTM", which integrates an additional convolutional layer, an autoencoder, and a layer of fusion of the functions of the attention mechanism into the architecture of the prediction network of convolutional long-term short-term memory (ConvLSTM) sequential images. This approach is aimed at predicting the propagation of cracks at different stages of hydraulic fracturing. But the questions related to the definition of the geometry of the crack remained unresolved. The likely reason is the difficulties associated with the use of universal software, which makes the relevant studies inaccurate.

In [7], a hybrid method of fracturing modeling was devised, which combines the advantages of the finite element method (FEM) and the peridynamic approach (PD). The authors proposed a comprehensive approach to modeling both rock deformation and fluid movement. The difficulty of implementation is the need to combine two different approaches. The study creates a basis for further improvement of fracturing modeling methods, especially in terms of predicting the development of complex fracture systems.

The main preparatory stage of hydraulic fracturing is checking the degree of development of natural destruction and the distribution of the stress field in situ [8]. Based on these observations, the question of determining the degree of natural destruction remains unresolved, namely the difficulty of predicting the behavior of cracks due to the incompleteness of data on the structure of natural fractures. Also, an unsolved problem is the impossibility of accurately determining local inhomogeneities of the stress field and the limitations of existing models when describing the interaction of natural and artificial cracks.

The design of hydraulic fracturing should ensure that the main crack extends as far as possible and continues the natural crack along its zone in saturated homogeneous porous rock as much as possible [9]. It is imperative to take into account the dynamic change in rock properties during the fracturing process. The authors did not consider cases of complex geometry of cracks, a simplified representation of the interaction between different types of fluids and their properties. After all, in fracturing modeling, an important role is played by the viscosity of the fluid for hydraulic fracturing and the injection rate, which are engineering factors that are most often used to control the morphology of hydraulic fracturing both in the laboratory and in the field [10]. But the following questions remained unresolved:

– the way the liquid viscosity affects the propagation of cracks in different types of rocks, especially under conditions of anisotropy (different rock strength in different directions);

– determination of the optimal speed, which makes it possible to maintain the stability of cracks without the risk of their closure due to stress dissipation;

– the way a change in injection speed affects the structure and permeability of the formed cracks.

All this gives reason to assert that the study of the influence of engineering and geological factors on the hydraulic fracturing process requires further detailed research. In particular, in order to ensure the efficiency of the fracturing process, it is necessary:

– to conduct experiments with different fluids for fracturing, taking into account their viscosity and chemical composition;

– to improve the accuracy of models, taking into account the complex geometry of cracks and the interaction between fluids and rocks;

– to establish the relationship between the injection speed and the length, permeability, and morphology of cracks;

– to expand the database on rock destruction pressures under different conditions;

– to investigate the stress-strain state of the rock during hydraulic fracturing.

Further research in these areas will help resolve existing uncertainties and improve the efficiency of hydraulic fracturing technologies, providing more reliable results in the field.

3. The aim and objectives of the study

The purpose of our study is to build a model of hydraulic fracturing for terrigenous reservoirs, taking into account geological and technical conditions and crack propagation patterns, which would make it possible to increase the efficiency of the hydrocarbon production intensification process.

This will make it possible to improve the filtering properties of terrigenous reservoirs, increase the productivity of wells, and obtain an economic effect from the implementation of this method of influence on productive layers.

To achieve the goal, the following tasks were set:

– to evaluate the filtration-capacity properties of the terrigenous reservoir, including its porosity, permeability, and lithological heterogeneity by thickness and area of the productive section;

– to investigate the process of destruction of rocks under the action of blowout pressure and to simulate the optimal geometry of the crack;

– to evaluate the effect of proppant concentration and volume on fracture conductivity and long-term productivity of wells;

– to estimate the conductivity parameters of the crack.

4. The study materials and methods

The object of our research for designing the hydraulic fracturing is well No. 4 at the Rakytnyanske gas field (Ukraine, in the territory of the Kharkiv oblast), which must be provided with the materials given in Tables 1, 2.

Table 1

Required amount of chemical reagents

Type of chemical reagent	Quantity
NG BioD – Bactricide	16.3 kg
NG NE-1 Non-Emulsifier	256 l
NG CS-2 Clay Stabilizer	256 l
NG GS-1 Temp Stabilizer	256 l
NG SG-1 Salt Stabilizer	128.2 kg
WGA NG-1 – Gelling agent	1,077.0 kg
30/60 BoroProp	20,419.5 kg
S100	3,000.0 kg
NG-B2 Encapsulation breaker	44.1 kg
NG-BK Live breaker	20.2 kg
XL-4 Crosslinker	812.0 kg
XL-6 Crosslinker	54.1 kg
HCL 13 %	3,000 l
Quartz flour	1,000 kg
20/40 SinLit	11,840.0 kg

Table 2

The need for water for intensification

Water requirement	Volume	Measurement unit
Basic hydraulic fracturing – XL35HTD, L35	112.0	m^3
Mini hydraulic fracturing – XL35HTD	23.3	m^3
Non-recoverable residue in containers	52	m^3
Total liquids	187.3	m^3
Pusher (basic hydraulic fracturing)	18.1	m^3
Pusher (mini hydraulic fracturing)	38.0	m^3
Non-removable residue in the container and for crimping	13	m^3
Total liquids	69.1	m^3
Total water required	256.4	m^3

Rakytnyanske gas field is one of those at a late stage of development. The reservoirs of productive horizons belong to terrigenous deposits and are lithologically composed of sandstones, clayey sandstones, less often siltstones with layers of argillites and limestones.

According to the results of thermodynamic studies of the B-20-21 horizon, its productivity was confirmed, but with weak gas release, during which stabilization of the wellhead pressures was not achieved. This indicated very low filtration properties (in particular, permeability) of the reservoir, so it was decided to perform fracturing using modern software.

Tables 1, 2 give the required amount of designed chemical reagents and water for fracturing, namely:

– NG BioD – Bactricide prevents the formation and development of bacteria in the hydraulic fracturing fluid;

– NG NE-1 Non-Emulsifier helps stabilize the system in a homogeneous state, preventing liquid stratification;

– NG CS-2 Clay Stabilizer prevents swelling of clay and dispersion, which reduces the risk of sludge formation and clogging of the porous medium;

– NG GS-1 Temp Stabilizer prevents liquid decomposition and phase separation at elevated temperatures;

– NG SG-1 Salt Stabilizer stabilizes fracturing fluid and prevents precipitation of salts;

– WGA NG-1 is a gelling agent that creates a viscous medium for holding the proppant in suspension, transporting it into the formed cracks and channels to the top of the fracture, and provides fluid flow control. Also, the viscosity created by the gelling agent provides sufficient width and control of the growth of the crack height.

Crosslinkers are agents that play an important role in the formation of a crosslinked gel by linking polymer chains.

Breakers are used to clean cracks and channels from hydraulic fracturing fluid, reducing viscosity; they destroy bonds between polymer molecules, thus causing gel degradation.

Our research hypothesis assumes that optimization of hydraulic fracturing parameters taking into account the geological and technical conditions of terrigenous reservoirs of the Rakytnyanske gas field could make it possible to create a crack with optimal geometry and conductivity. As a result, this would lead to a significant increase in well productivity.

The terrigenous reservoirs of the Rakytnyanske gas field have sufficient potential for successful fracturing, and the use of innovative fluids for fracturing will make it possible to create a fracture with the necessary parameters. The use of FracCADE software makes it possible to reliably model the process of formation and development of cracks in the productive reservoir.

In simulation, the formation of one main crack is considered, not taking into account the possible formation of additional branches and microcracks; the reservoir is considered as a relatively homogeneous environment within the fracturing zone. Also, possible changes in the physical and mechanical properties of rocks during long-term operation of the well after hydraulic fracturing are not taken into account. Averaged values of permeability and porosity of the reservoir are used in the calculations.

5. Results of hydraulic fracturing design research

5. 1. Evaluation of the filtration-capacity properties of the terrigenous reservoir, including its porosity, permeability, and lithological heterogeneity by thickness and area of the productive section

The filtration capacity properties of terrigenous reservoirs are key parameters that determine the productivity of oil and gas wells. They characterize the ability of reservoir rocks to pass fluids (oil, condensate, gas, water) and retain them in their volume.

Based on the results of interpreting the materials of hydrodynamic studies on wells (HSW) and core research in well No. 4 at Rakytnyanske gas field, the following characteristics were obtained, given in Table 3:

Table 3

Reservoir properties of the productive horizon B-20-21 of well No. 4 at Rakytnyanske gas field

No. of saturation layer	Occurrence interval	Porosity, k_p, %	Oil and gas saturation, k_{go}, %	Effective thickness, h_{ef}, m	The nature of saturation
53	4,283.2–4,284.4	7.5	80	0.6	Compacted gas-saturated
54	4,286.8–4,287.6	6.5	–	–	Compacted gas-saturated
55	4,287.6–4288.0	8.0	65	0.4	Compacted gas-saturated
56	4,288.6–4,290.6	6.0-9.5	78	1.4	Gas-saturated
57	4,291.0–4,292.0	10.0	75	1.0	Gas-bearing
58	4,293.0–4,296.2	7.5–9.5	83	~2.0	Compacted gas-saturated

According to laboratory data, permeability k varies from $7\cdot10^{-15}$ to $35\cdot10^{-15}$ m^2.

Baes on the given values of porosity and gas saturation, the reservoir can be classified as a porous reservoir.

The studied layers are lithologically represented by sandstones of different clay content with interlayers of argillites. The porosity of the formations ranges from 6.5 to 10 %, which indicates the average quality of the reservoir. Given the above-mentioned lithological heterogeneity, small fluctuations in porosity and gas saturation are observed in different strata.

The formations are mainly compacted and gas-saturated, although gas-bearing and gas-saturated character is observed in some intervals. This indicates that the gas in the formation is in a free state and partly in an adsorbed state.

Based on the data provided, it can be concluded that the formation in the depth range of 4,283.2–4,296.2 m is a porous gas-saturated reservoir with low or medium porosity and low or reduced permeability.

5. 2. Investigating the process of destruction of rocks under the action of punching pressure and modeling of the optimal geometry of the crack

The following algorithm was used when designing fracturing for the conditions of the terrigenous reservoir at Rakytnyanske gas field using the FracCADE software:

1. Calculation of the pressure on the holes during hydraulic fracturing.
2. Calculation of the parameters of the liquid-sand mixture.
3. Calculation of pressure losses due to friction during the movement of the mixture along the tubing.
4. Determination of the required pressure at the wellbore during the fracturing process.
5. Carrying out verification calculations of the tubing for the allowable pressure at the wellbore.
6. Carrying out verification calculations of the casing string for the permissible pressure at the wellbore (for the case of tubing descent without a packer).
7. Determination of the required number of units.
8. Calculation of the required amount of materials.
9. Calculation of unit operation.
10. Assessment of process efficiency.

As a result, we obtained the following characteristics, which are given in Table 4.

They indicate that we obtained a larger half-length of the actual crack of 136.9 m in comparison with the parameter during modeling – 110.2 m, and also, as a result, a larger actual fixed half-length – 109.0 m against 102.0 m in simulation. But the total height of the break and the total fixed height turned out to be smaller, 36.5 m and 14.0 m, respectively, compared to the similar design parameters – 43.6 m and 20 m.

Fig. 1 shows the geometry of the crack that will be formed during the basic hydraulic fracturing.

Fig. 2 shows graphical dependence of the passage of liquid through the crack formed during basic hydraulic fracturing.

Also, the actually formed crack has a smaller and average width of 0.148 cm, in simulation – 0.197 cm. That is, in general, it can be stated that as a result of hydraulic fracturing, a longer crack was formed than was projected with reduced profile geometry parameters.

Table 4

Crack geometry

Parameter	Value
Crack half length (m)	136.9
Total height of gap (m)	36.5
Vertical depth to the upper limit of the crack (m)	4277
Vertical depth to the lower limit of the crack (m)	4,313.5
Equivalent number of cracks formed	1.0
Effectiveness of the mixture for breaking	0.233
Average proppant concentration (kg/m^2)	2.57
Fixed half-length (m)	109.0
Total fixed height (m)	14.0
Vertical depth to the upper limit of the fixed crack (m)	4,284.2
Vertical depth to the lower limit of the fixed crack (m)	4,297.9
Maximum crack width (cm)	0.374
Average crack width (cm)	0.148

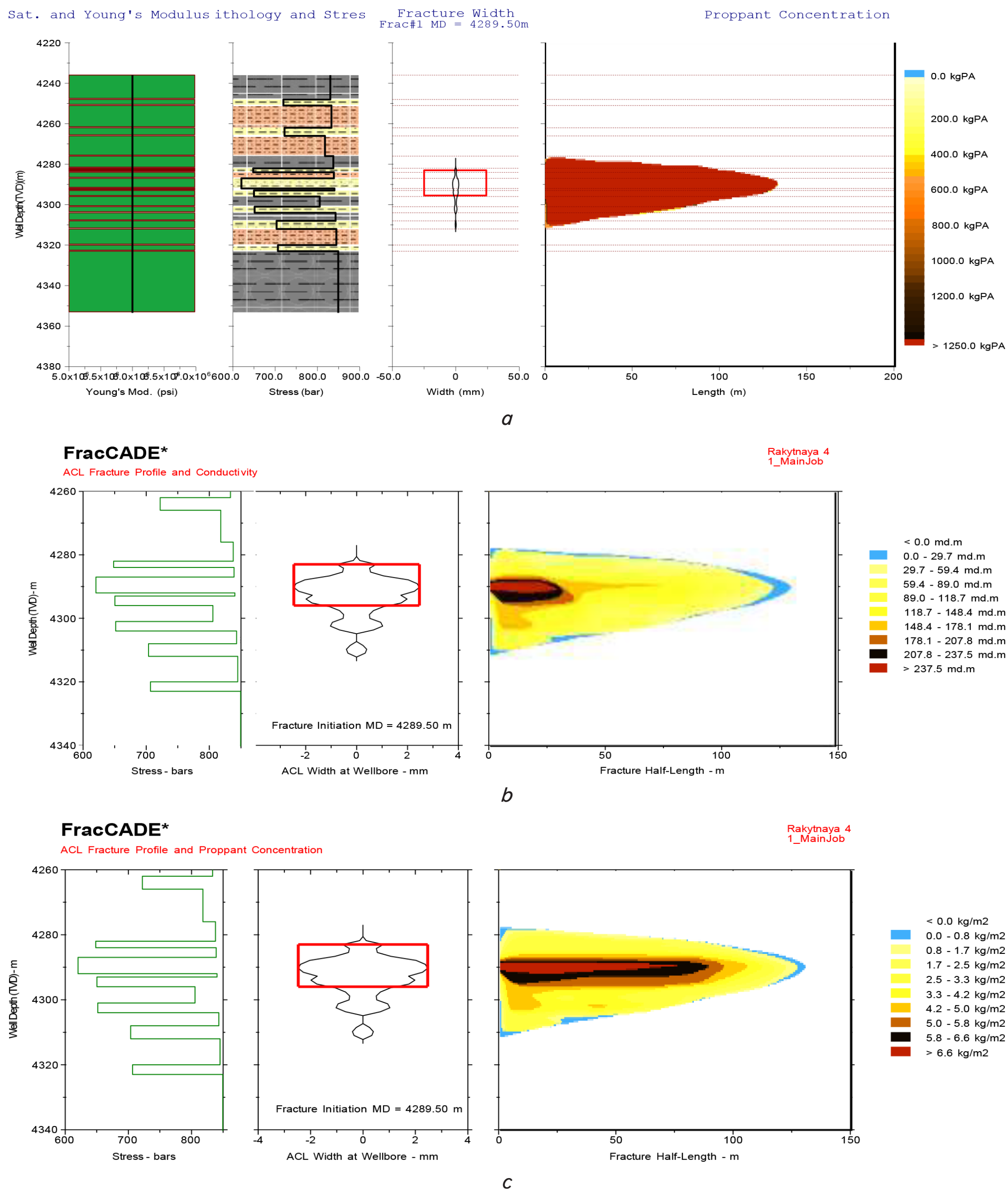

Fig. 1. Result of crack formation during basic hydraulic fracturing: *a* – the simulated shape and geometry of the real crack as a result of basic hydraulic fracturing; *b* – profile of a real crack and its conductivity along the length as a result of modeling; *c* – the profile of a real crack and the change in proppant concentration along its length as a result of modeling; young's mood (psi) – Young's module; stress (bar) – stress; Width (mm) – crack width; Length (m) – crack length; Well depth (m) – well depth; Fracture half-length (m) – half-length of a crack; ACL Width at Wellbore (mm) – the width of the crack in the wellbore zone at a depth of 4289.5 m

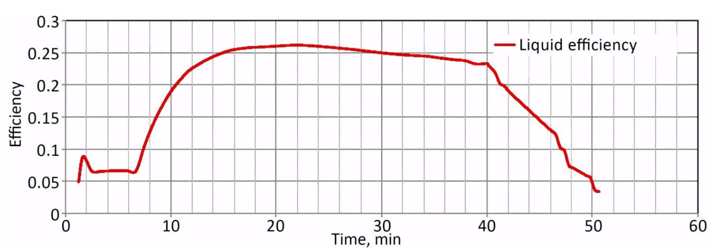

Fig. 2. Graphic dependence of the passage of liquid through the crack formed during basic reservoir hydraulic fracturing

5. 3. Evaluating the influence of proppant concentration and volume on fracture conductivity and long-term productivity of wells

Fig. 3 shows graphical dependence of the pressure change in the process of proppant injection depending on its concentration during basic hydraulic fracturing.

As a result, a smaller amount of proppant was pumped into the crack (23.88 t) than the expected 31.76 t. Accordingly, the average proppant concentration was 2.57 kg/m^2, which is not significantly less than the design value of 3.2 kg/m^2 but is still sufficient and will contribute to the effective extraction of hydrocarbons.

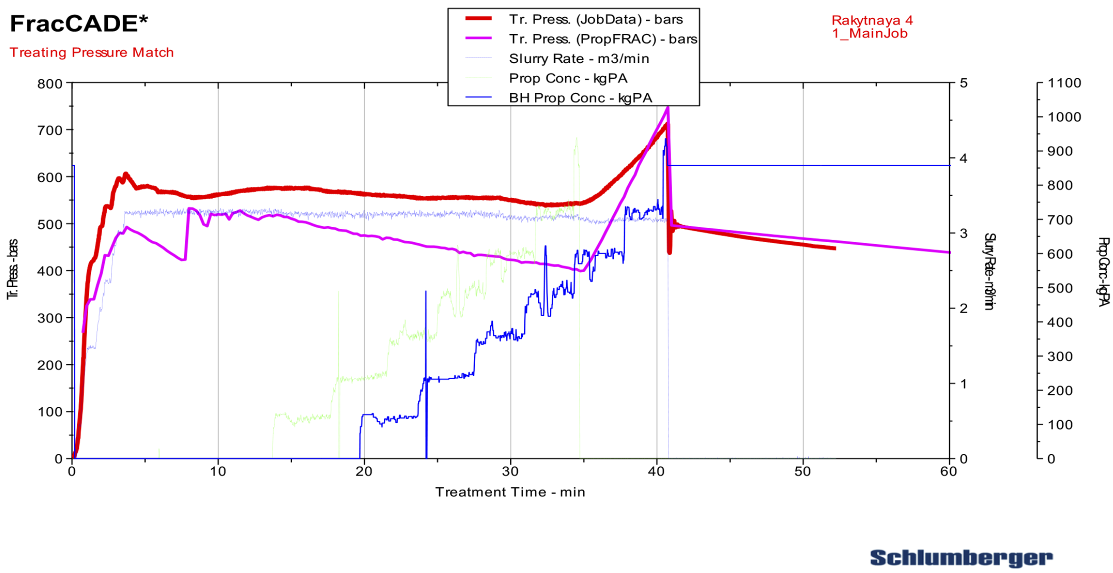

Fig. 3. Plot of pressure changes in the process of proppant injection depending on its concentration during basic hydraulic fracturing: Tr. press (JobData) – wellbore pressure, which is registered in the pipe space; Slurry Rate – productivity of injecting the mixture of gel and proppant into the well; Prop Conc – proppant concentration during mixing; BH Prop Conc – proppant concentration at the wellbore

5. 4. Estimation of crack conductivity parameters

According to the data in Tables 5, 6, the average value of the conductivity of the crack is 152 mD·m, which is not significantly less than the design assumption during modeling (157.0 mD·m). Both the project and actual indicators obtained are not high enough but sufficient to achieve a positive effect. The dimensionless conductivity is 1.1, which is a relatively average indicator at which the reservoir will perform optimally for a given amount of proppant. The data in Table 5 indicate that the crack was formed at a fairly high average pressure at the wellhead of 560 kgf/cm^2. At the same time, the hydraulic fracturing crack closure pressure on the well was 612 kgf/cm^2.

Based on the resulting data given in Tables 7, 8, it is possible to calculate the predicted flow rate of the well; and it was between 1.1 thousand m^3/day up to 123.4 thousand m^3/day.

Table 7 gives the data obtained according to the geological section of the productive horizon where hydraulic fracturing was performed. Specifically:

– SHALE – fine-grained sedimentary rock consisting of silt, which is a mixture of clay minerals and dust-sized particles;

– DIRTY-SANDSTONE – a type of sandstone that contains a significant amount of clay or silt mixed with sand grains;

– SILTSTONE – a sedimentary rock consisting mainly of dust-sized particles. It has a finer grain size than sandstone, but coarser than SHALE.

Therefore:

– the crack formed as a result of hydraulic fracturing is long and high;

– the crack has a relatively average conductivity;

– the crack is fixed and stable for filtering reservoir fluids.

Table 5

Aggregated data on crack formation pressure

Parameter	Value
Effective pressure of the model (kgf/cm^2)	174.3
Actual effective pressure (kgf/cm^2)	–
Hydrostatic pressure (kg/cm^2)	421.3
Formation pressure (kg/cm^2)	210
Hydraulic fracturing crack closure pressure on wells (kgf/cm^2)	612.2
Closing pressure gradient (kPa/m)	14.46
Average pressure at the wellbore (kgf/cm^2)	560.0
Maximum pressure at the wellbore (kgf/cm^2)	710.0

Table 6

Crack conductivity parameters

Parameter	Value
Average value of conductivity (mD·m)	152
Dimensionless conductivity	1.1
Proppant damage coefficient	0.643
Perceived damage factor	–
Total damage factor	0.643
Effective fixed length (m)	–
The average value of the crack width (closed on proppant) (cm)	0.374
Relative permeability of the formation (mD)	1.0
Permeability of intact proppant under stress (mD)	121834
Proppant permeability, taking into account proppant damage (mD)	43467
Proppant permeability, taking into account total damage (mD)	43467
Proppant depression (mm)	–

Table 7

Crack geometry for calculating predicted flow rate

Reservoir	Roofing along the trunk	Roofing along the spinner	Capacity	Effective capacity	Crack width	Half-length of crack	Conductivity
Units	m	m	m	m	mm	m	mD·m
SHALE	4236.0	4236.0	12.0	0.0	0.0	0.0	0.0
DIRTY-SANDSTONE	4248.0	4248.0	3.0	0.0	0.0	0.0	0.0
SILTSTONE	4251.0	4251.0	11.0	0.0	0.0	0.0	0.0
DIRTY-SANDSTONE	4262.0	4262.0	4.0	0.0	0.0	0.0	0.0
SILTSTONE	4266.0	4266.0	10.0	0.0	0.0	0.0	0.0
SHALE	4276.0	4276.0	6.0	0.0	0.2	82.4	10.4
DIRTY-SANDSTONE	4282.0	4282.0	2.0	2.0	0.8	108.9	40.2
SILTSTONE	4284.0	4284.0	3.0	0.0	1.4	127.1	75.3
DIRTY-SANDSTONE	4287.0	4287.0	5.0	5.0	3.7	136.9	204.0
SILTSTONE	4292.0	4292.0	1.0	0.0	3.2	136.5	173.0
DIRTY-SANDSTONE	4293.0	4293.0	3.0	3.0	2.7	131.1	141.0
SHALE	4296.0	4296.0	5.0	0.0	0.9	118.7	51.2
DIRTY-SANDSTONE	4301.0	4301.0	3.0	3.0	0.8	88.5	45.1
SHALE	4304.0	4304.0	4.0	0.0	0.1	69.8	6.6
DIRTY-SANDSTONE	4308.0	4308.0	4.0	4.0	0.0	28.6	3.2
SILTSTONE	4312.0	4312.0	8.0	0.0	0.0	19.3	0.0
DIRTY-SANDSTONE	4320.0	4320.0	3.0	3.0	0.0	0.0	0.0
SHALE	4323.0	4323.0	30.5	0.0	0.0	0.0	0.0

Table 8

The actual geometry of the fixed crack and its conductivity along the segments

From	To	Proppant concentration at the end	Fixed width	Fixed height	Proppant concentration	Gel concentration	Conductivity of crack
m	m	kgPA	mm	m	kg/m^2	kg/m^3	md·m
0.0	34.2	858.5	1.3	10.6	2.3	165.6	189.3
34.2	68.5	958.7	1.7	27.0	2.9	126.6	94.4
68.5	102.7	1018.7	2.0	22.1	3.5	101.0	85.7
102.7	136.9	296.0	0.9	12.4	1.6	403.3	39.7

However, it should be noted that this forecast is only approximate. The actual flow rate of the well may differ from the predicted one depending on such factors as:

– real geometric characteristics of the fixed crack;

– actual conductivity of the formed crack;

– mechanical properties of the reservoir;

– well operation mode, etc.

6. Discussion of results based on reservoir hydraulic fracturing

Our results of the study of filtration and capacity properties can be explained by the following factors:

– in contrast to homogeneous reservoirs [2], lithologically heterogeneous terrigenous deposits (sandstones of varying clay content with layers of argillites) indicate the continental origin of the rocks, and their considerable depth of occurrence (4283–4296 m) (Table 3) led to compaction of the rocks under the action of geostatic pressure;

– different effective capacity (thickness) of layers (0.4–2.0 m) (Table 3) indicates the difficulty of hydrocarbon extraction;

– variable clay content of sandstones affects porosity fluctuations (6.5–10 %), and the presence of mudstone layers creates additional barriers for filtration.

Low values of permeability ($7 \cdot 10^{-15}$–$35 \cdot 10^{-15}$ m^2) (Table 3) are explained by the significant compaction of rocks at great depth, the presence of clay cement, the contamination of the porous medium, and the complex structure of the pore space.

The presence of both free and adsorbed gas indicates the complex nature of gas saturation. At the same time, relatively high indicators of gas saturation (mainly 75–83 %) (Table 3) with relatively low porosity indicate good shielding properties of grinding.

The discrepancies between the simulated and actual parameters of the crack indicate stress anisotropy in the reservoir, which could have contributed to the preferential development of the crack in length (136.9 m vs. 110.2 m) (Table 4), in contrast to a report [5] that stress anisotropy of the material directs the crack to the weakest plane. It was also established that the vertical heterogeneity of the mechanical properties of the rocks limited the height of the break (36.5 m versus 43.6 m) (Table 4).

The real behavior of the fracture fluid (Fig. 2) could differ from the model due to the different viscosity of the fluid in different parts of the fracture. This is also confirmed by uneven pressure distribution and filtration losses in the formation, as evidenced by the obtained smaller average crack width (0.148 cm vs. 0.197 cm) (Table 4).

The different strength of the rocks along the section determined the actual geometry of the crack (Fig. 1), and the clay content of the reservoir affected the effectiveness of the crack anchoring. The layering of the section (alternation of SHALE, DIRTY-SANDSTONE, SILTSTONE) affected the propagation of the crack (Table 7), and the proppant concentration (2.57 kg/m^2) affected the fixed geometry of the crack (Table 4, Fig. 1).

The decrease in the amount of injected proppant was influenced by the actual geometry of the crack, which differed from the design one (longer but narrower), as well as the need to control the injection pressure (Fig. 3).

Our result regarding the proppant concentration and volume can be explained by the following:

– optimization of proppant consumption while maintaining the efficiency of the operation;

– ensuring uniform placement of proppant (by concentration) at the moment when the first portion of the working mixture (with proppant) reaches the top of the crack;

– ensuring sufficient conductivity even with a concentration of 2.57 kg/m^2.

This result demonstrates that even with a smaller amount of injected proppant, the necessary parameters for efficient well operation can be achieved.

The productive half-length of the crack (fixed half-length) is equal to 109.0 m, which is slightly less than the created half-length of 136.9 m (Table 4). This can be explained by several main reasons:

– the width of the crack near the top turned out to be insufficient to fill it with proppant in an appropriate manner;

– vertical heterogeneity of the layer in terms of permeability or rock composition.

The obtained simulation result regarding fracture conductivity parameters is explained by several factors, in contrast to multifactor modeling [7], which affect the characteristics of the hydraulic fracturing process (fracking) and the resulting efficiency.

The resulting average value of the actual fracture conductivity of 152 mD·m (Table 6) can be explained by some damage to the proppant. After all, the proppant damage coefficient is 0.643 (Table 6), which indicates the loss of permeability due to mechanical crushing or chemical interactions.

The average pressure at the wellbore (560 kgf/cm^2) and closing pressure (612 kgf/cm^2) (Table 5) indicate significant factors:

– local stresses;

– stress gradients;

– stress differences between different geological layers;

– differences in tensile strength between different layers.

This indicates that the rocks have high strength and some of the energy spent on crack initiation has reduced the crack opening efficiency.

Productive horizons include rocks of the SILTSTONE, DIRTY-SANDSTONE, and SHALE types (Table 7), which have different permeability and filtration properties. Most of the proppant may have settled in less permeable rocks (SHALE), limiting conductivity in key zones with high production potential.

The resulting fracture is long and tall, but a significant part of its productive length (over 102 m) and height has a relatively low width (<1.0 mm) (Table 8 and Table 7), respectively, which limits the overall conductivity. Proppant concentration is unevenly distributed, which also contributes to heterogeneous conductivity.

Our study offers solutions for conducting fracturing in complex terrigenous reservoirs, including analysis of anisotropy, rock heterogeneity, optimization of proppant consumption, and consideration of real fracture fluid behavior.

However, the following limitations should be considered:

– design models do not take into account all geological inhomogeneities and possible losses of proppant due to gravitational sedimentation or uneven transportation;

– the actual geometry of the crack (longer, but narrower) affected the decrease in the amount of injected proppant. This required control over the injection pressure but resulted in a trade-off between crack length and crack width;

– uneven concentration of proppant in the fracture reduces its conductivity and limits the effectiveness of formation filtration.

Disadvantages of hydraulic fracturing parameters forecasting include the following:

– incorrect selection of the composition and volume of fluid for hydraulic fracturing can lead to a decrease in the efficiency of creating cracks, contamination of the reservoir, and complications during further production;

– an inaccurate forecast of the height, length, width, and orientation of cracks can lead to inefficient coverage of the layer (interlayers) and obtaining a slight increase in well productivity;

– design models do not take into account all aspects of geological heterogeneity, especially the change in clay content and the presence of argillite layers, which significantly affect the propagation of cracks and their conductivity;

– incomplete assessment of geological, technical, and environmental risks (pollution of groundwater, flora and fauna and emissions of harmful substances into the atmosphere) [11] can also lead to unforeseen complications during hydraulic fracturing.

Further development of the research involves solving and improving the development of more accurate crack propagation models, analysis of proppant distribution in the crack.

Current models do not take into account sufficient stress anisotropy, vertical rock heterogeneity, and variable fracture fluid behavior. More accurate models will allow better prediction of fracture geometry and optimization of fracturing parameters, which will improve the efficiency of operations.

Nonuniform proppant distribution is a key factor limiting fracture conductivity. Studying the mechanisms of sedimentation, loss of proppant, and its transportation could make it possible to reduce the damage coefficient and improve the effectiveness of crack fixing.

Future research should focus on improving models, investigating fluid-rock interactions, optimizing proppant distribution, and expanding geography and reservoir types. This would solve existing limitations, improve the efficiency of hydraulic fracturing, and make the results more universal for application under different conditions.

7. Conclusions

1. The productive layer exploited by well No. 4 is a compacted gas-saturated reservoir with low to medium porosity and low to reduced permeability. In the depth range of 4283.2–4296.2 m, it is a medium-quality porous gas-saturated reservoir.

2. The conducted fracturing was successful and led to the formation of a crack that meets general expectations. The crack has a fixed length (109.0 m), a total fixed height of 14.0 m, and

an average width of 0.148 cm, which indicates the effectiveness of the fracturing technology.

3. The achieved proppant concentration of 2.57 kg/m^2 indicates that the main fracture was well filled with proppant (23.88 t was pumped), and this in turn provided the fracture conductivity with an average value of 152 mD·m.

4. The hydraulic fracturing operation was successful, although the conductivity of the created fracture could have been higher. The resulting conductivity and pressure values indicate that the created main crack and the system of small channels enabled an increase in the productivity of the well after the intensification, namely, the flow rate increased from 2.72 thousand m^3/day up to 100 thousand m^3/day.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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