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Improving the formulation of hydraulic fracturing fluid

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Abstract. The growing need to increase production of natural hydrocarbons makes hydraulic fracturing technology one of the key methods of production stimulation, so the need to improve the efficiency and cost-effectiveness of hydraulic fracturing, which can be achieved by optimising the fluid composition, is becoming an urgent issue. The aim of the study was to find effective formulations of hydraulic fracturing fluid that would have the structural and rheological properties necessary for successful hydraulic fracturing in wells with temperatures above 80°C. An empirical method of conducting laboratory studies of hydraulic fracturing fluid formulations is used. To substantiate the rheological properties of hydraulic fracturing fluids, they were tested. This method involved systematic testing of various combinations of fluid components to select the optimal composition that would meet the requirements of efficient and economical fracturing at elevated well temperatures. The main types of fracturing fluids and their formulations are analysed, and the results of laboratory studies on the selection of optimal parameters of fracturing fluid in a well with a formation temperature of 85°C are presented. The relationship between the chemical composition (formulation) of the fracturing fluid and its rheological properties at a temperature of 85°C is experimentally established. Using the method of formulation selection, the composition of the fracturing fluid was found that can withstand landslide pressures, is stable and does not collapse prematurely. The article proposes a formulation of a fluid that can be used during hydraulic fracturing in gas and oil fields. Practical implementation of the research results will improve the efficiency of hydraulic fracturing technology and increase the productivity of oil and gas wells

Keywords: bottomhole formation zone; well; fracking; linear gel; laboratory fluid tests; polymers

Introduction

Hydraulic fracturing is a widely used technique to stimulate hydrocarbon production by creating a network of highly conductive fractures in the area around the wellbore and in the remote reservoir zone. The created network of fractures not only improves the conductivity of the reservoir rock, but also increases the filtration surface area, which helps to intensify hydrocarbon production. This method can be used in both vertical and horizontal wells. Oil and gas companies are working to develop the most effective fluid composition to achieve the best possible reservoir conductivity after the operation. Linear or cross-linked guars are the most commonly used fluids in traditional fracturing operations (Zhao *et al.*, 2020). The main functions of these fluids are to form or open a crack (a fracture) and transport propane through the crack (Almubarak *et al.*, 2020). To maintain gel stability at the end of the fracturing process, various chemicals are used. During fracturing in high temperature wells, conventional guar-based polymer systems degrade faster than at low temperatures and require more guar to maintain stability, as indicated by

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Y. Huang *et al*. (2024). However, increased concentrations of guar in the fluid lead to an increase in residual decay products after destruction and, as a result, to contamination of the bottomhole formation zone and the formation as a whole, as reported by S. Liu *et al*. (2020). To solve these problems, various high-temperature stabilisers are added to improve the thermal stability of these fracturing fluids at temperatures above 85°C.

The chemical composition of hydraulic fracturing fluids mainly includes polymer systems, cross-linking agents, bactericides (biocides), breakers, buffers, clay stabilisers, deflectors, friction reducers, gel stabilisers, surfactants and demulsifiers, and temperature stabilisers (Wang *et al*., 2022a; 2022b). To obtain a high viscosity of the linear gel, polymers are used. L. Moroz *et al*. (2023) emphasised the importance of each chemical in the gel structure. Cross-linkers are used to bind polymer molecules together. Destructors (breakers) are added to break the bonds between the polymer molecules in the formation and cause its dehydration. Clay stabilisers are used to prevent clay swelling. Demulsifiers are used to prevent emulsion formation and reduce surface tension. Buffer solutions are used to control the pH, acidity or alkalinity of the solution, which affect the hydration of the polymer, the quality and the cross-linking time. For high temperatures, temperature stabilisers are used. Defoamers prevent foam formation. Friction reducers are used to reduce pressure losses during pumping. Insulating agents are also used to isolate the processing interval at the top and bottom.

To select fracturing fluid compositions for specific well conditions, it is important to experimentally determine the stability of their rheological characteristics, as indicated by H. Xu *et al*. (2023) over the expected period of hydraulic fracturing operations and their post-operational decomposition time, simulating reservoir conditions. This process involves taking into account the geological and operational characteristics of the well, including reservoir filtration properties, reservoir temperature, pressure and sensitivity of the reservoir rocks to fracturing fluid. In fact, according to A.K. Quainoo *et al*. (2022), this process highlights the need for a comprehensive understanding and tailored approach to hydraulic fracturing operations, emphasising the critical role of adapting fluid formulations to the unique conditions of each well. By carefully evaluating the rheological properties of fracturing fluids under conditions that mimic the surrounding formation properties, engineers can improve the efficiency and effectiveness of the fracturing process. This approach not only improves hydrocarbon production, but also minimises potential negative effects on reservoir performance and environmental impact. Experimental determination of fluid stability and rheological properties requires sophisticated laboratory equipment and methodologies that can accurately reproduce the high pressure and high temperature conditions in deep underground reservoirs. In addition, understanding the sensitivity of the reservoir rock to fracturing fluids is paramount to avoiding a reduction in permeability that could impede hydrocarbon flow to the wellbore, as discussed in paper by S. Al-Hajri *et al*. (2022).

Overall, optimising the fracturing fluid based on detailed reservoir characteristics and precisely executing fracturing operations is fundamental to maximising oil and gas production. An analysis of various studies indicates that although considerable work has been done to develop and optimise hydraulic fracturing fluids, the aspect of creating effective fluids without the addition of temperature stabilisers with minimal polymer loads and studying their rheological effects remains insufficiently researched. This indicates the potential for further research in this area, especially given the growing demands for environmental safety and efficiency of hydrocarbon production processes. This work is aimed at finding a combination of chemical elements to create fracturing fluids without the addition of temperature stabilisers at minimal polymer loads and studying their rheological effects.

Materials and Methods

Laboratory tests were carried out, with a combination of different formulations of chemicals and their quantities. The following equipment was used in the laboratory: an aerometer designed to determine the density of the liquid; a blender used to mix chemicals; electronic scales for accurate measurement of the amount of chemicals; an acidity meter with a temperature sensor for determining pH and temperature; an Ofite viscometer (800S model, Ofite Company, USA) for determining viscosity; a Brookfield rheometer (PVS model, Brookfield Company, USA) for determining viscosity under specified reservoir conditions. All instruments in the laboratory are certified and periodically calibrated. Laboratory tests were carried out to find the optimal formulation parameters aimed at reducing and avoiding formation contamination with additional polymer degradation products. The aim was to achieve the required rheological properties of hydraulic fracturing fluids, in which the system would be stable, restore its rheological properties after phase loads and not be prematurely destroyed. This article describes the step-by-step formulation tests for fracturing fluids. The article considers the most common chemical composition of water-based fracturing fluid in Ukraine (Table 1). A test was carried out in the laboratory to select the optimal parameters of the fracturing fluid at a temperature of 85°C.

Table 1. Names of chemicals used in the study

S	Salt stabiliser	Sodium D-gluconate (80%), crystallised silicon dioxide (20%)
W	Accelerated cross-linker	Ethylene glycol (30%), sodium tetraborate (30%), water (40%)
D	Slow cross-linker	Ulexite (55%), diesel fuel (45%)

Table 1. Continued

B	Bactericide	2, 2-dibromo-2-cyano acetamide (80%), sodium glucate (10%)
N	Gelling agent	Guar gum/resin, guar
G	Clay stabiliser	Ethylene glycol (30%), choline bicarbonate (50%), water (20%)
X	Demulsifier of surfactants	Mixture of surfactants (75%), water (20%), ethylene glycol (5%)
C	Liquid destructor	Ammonium persulfate
Z	Encapsulated destructor	Encapsulated ammonium persulfate

Source: created by the authors

The water tests were conducted, which were used to prepare the fracturing fluid. The next step was a test to increase the viscosity of the linear gel and a cross-linking test. After that, the fluid was tested on a rheometer, which performed stability, shear and fracture tests. The water was tested for compatibility with the chemicals used in the process according to API RP 45: Recommended practice for analysis of oilfield waters (1998), according to which water was tested for chemical and mechanical impurities, which included the following items, and API RP 39: Recommended practices on measuring the viscous properties of a cross-linked water-based fracturing fluid (1998). Determination of water purity, colour and transparency. Determination of the salt content: the percentage of salt in water should not exceed 1.5%, otherwise the gel will quickly dehydrate. Determination of iron content (Fe): the amount of iron in the water should not exceed 10 mg/l, if this amount is exceeded, partial cross-linking of the polymer is recorded, and the overall quality of the cross-linked gel deteriorates. Determination of sodium (Na^+), potassium (K) and chloride (Cl^-) content: if the water content is high, the gel is cross-linked; the value should be less than 500 mg/l. Determination of alkalinity, bicarbonate content (HCO_3^-): it affects the hydration of the polymer and increases the cross-linking time of the gel at high rates. Determination of rigidity: determined by the content of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the water, with a large amount affects the gel cross-linking time, increasing it. Determination of the content of sulfates (SO_4^{2-}): the high content of sulfates contributes to the formation of dense insoluble mineral deposits. Determining the pH level, which should be between 6.0 and 8.0: if the pH is below 6.0, this leads to a lack of cross-linking, if it is above 8.0, then the linear gel cross-links too quickly. The test is carried out by dipping a strip of litmus paper, a universal indicator, into water. After one or two minutes, the changed colour of the indicator paper is compared with the colour of the scale provided in the kit.

In order to thicken the water to form a linear gel (linear gel viscosity test), 4 tests were performed, including 3 tests with a gelling agent loading of 2.8 kg/m^3 and one test with a loading of 3.0 kg/m^3. The research (test) methodology is as follows: pre-selected water for hydraulic fracturing was heated to a temperature of 50 degrees. Then it was transferred to a blender cup in a volume of 0.5 m^3. The gelling agent was added and hydration was carried out for 6.5 min with the blades in the blender rotating at 300 rpm. The gel was then transferred in a volume of 400 ml to an Ofite viscometer. During the test, the temperature, pH of the water and gel, hydration time, and viscosity before and after the addition of guar were recorded. The methodology for the linear gel cross-linking test was as follows: the linear gel was transferred to a 0.5-litre blender cup. A cross-linker was added and hydration was carried out with the blades in the blender rotating at 2,000 rpm. After adding the cross-linker and chemical reagents to the linear gel, the temperature, dome formation time, funnel closure time, and cross-linking time were recorded. A combination of a slow and fast borate cross-linker was used for cross-linking. The shear rate (cross-linked gel shear test) has units of rpm. A Brookfield rheometer was used to measure the shear rate. The rheometer uses a rotating cup and a fixed rod with a gap between them to simulate a flow transition. The speed of rotation of the cup provides the shear rate, and the rod measures the shear load or resistance force acting on the walls of the cup and rod (Montgomery, 2013). This is determined by measuring the torque on the rod. The shear rate is the relative velocity between the stationary rod and the rotating cup divided by the separation gap. In the test, after the cross-linking test, the sample was transferred to the cup and sheared at a constant speed of 100 rpm until the temperature was brought to equilibrium. After heating the liquid, the speed increased to 500 rpm. This was repeated at least 4 times in the range of 100-500-100-500 rpm. The chemical composition given in Table 1 was used for the study and Tests 1, 2, 3, 4 were performed with the chemical reagent loads given in Table 2.

Table 2. The chemical reagent loads, Tests 1-4

Value	Test 1	Test 2	Test 3	Test 4
N, kg/m^3	2.8	2.8	2.8	3.0
G, l/m^3	2.0	2.0	2.0	2.0
X, l/m^3	1.0	1.0	1.0	1.0
S, kg/m^3	-	0.6	0.5	0.5
D, l/m^3	2.5	2.5	2.2	2.2
W, l/m^3	1.0	1.0	1.0	1.0

Source: created by the authors

The main stages of testing the stability of the cross-linked gel were as follows. A sample of the cross-linked gel was taken and transferred to a Brookfield rheometer. The sample chamber recreates reservoir conditions, pressure and temperature that are as close as possible to those that occur during hydraulic fracturing. During the exposure, it is necessary to monitor changes in the structure and properties of the gel, whether the system behaves consistently for 1 hour. At the end of the exposure, the test results should be analysed. If the gel remains stable and retains its properties, it can be used in the hydraulic fracturing process. If signs of destruction are found, it is necessary to change the gel formulation and retest. Since this fluid was selected for high-temperature wells, 3 stability tests (5, 6, 7) were performed at 85°C with the parameters given in Table 3. The cross-linked gel destruction test is carried out in the same way as the stability test, but with the addition of a destructor. Liquid (Z) and encapsulated (C) breakers were used for destruction (Table 4).

Table 3. The chemical reagent loads, Tests 5-7

Value	Test 5	Test 6	Test 7
N, kg/m^3	2.8	3.0	2.8
G, l/m^3	2.0	2.0	2.0
X, l/m^3	1.0	1.0	1.0
S, kg/m^3	0.5	0.5	0.6
D, l/m^3	2.2	2.2	2.5
W, l/m^3	1.0	1.0	1.0

Source: created by the authors

Table 4. The chemical reagent loads, Tests 8-10

Value	Test 8	Test 9	Test 10
N, kg/m^3	2.8	3.0	2.8
G, l/m^3	2.0	2.0	2.0
X, l/m^3	1.0	1.0	1.0
S, kg/m^3	0.5	0.5	0.6
D, l/m^3	2.2	2.2	2.5
W, l/m^3	1.0	1.0	1.0
Z, kg/m^3	0.2	0.2	0.2
C, kg/m^3	0.035	0.015	0.07

Source: created by the authors

Results

Water testing for compatibility with the chemicals used. Hydraulic fracturing requires a large amount of water. It is necessary that the water from a particular source meets certain acceptable parameters. For this purpose, before each hydraulic fracturing operation, water from each source is delivered to the laboratory and a number of tests are carried out. Figure 1 shows the colour of the indicator (arrow on the left) after reacting with water and comparing it to the colour of the scale (arrow on the right). The results of the content of calcium and magnesium bicarbonates, sulphates, chlorides, phosphates and iron ions in the liquid used in the following tests are shown in Table 5. It can be concluded that this water is suitable for the preparation of hydraulic fracturing fluid after conducting the following tests according to API RP 39: Recommended practices on measuring the viscous properties of a cross-linked water-based fracturing fluid (1998).

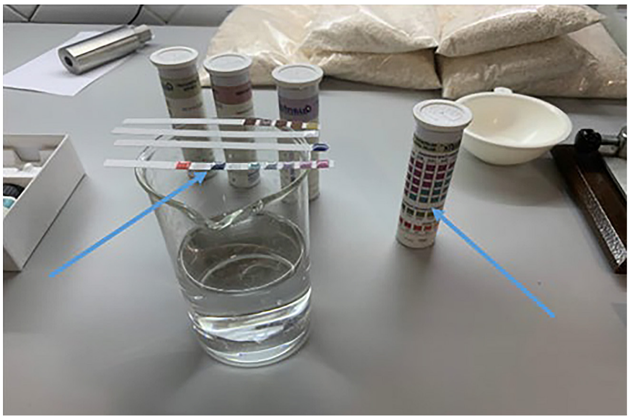

Figure 1. Testing water for substances

Source: created by the authors

Table 5. Testing water for impurity content

Value	Unit of measurement	Result	Norm
Density (25°C)	g/cm^3	0.998	1.005
pH	-	7.7	5-8.6
Na^+, K^+	mg/l	378.8	< 500
Ca^{2+}	mg/l	12	< 500
Mg^{2+}	mg/l	1	< 500

Table 5. Continued

Value	Unit of measurement	Result	Norm
Fe	mg/l	0	< 8
SO_4^{2-}	mg/l	80.3	< 100
Cl^-	mg/l	310.5	< 1,000
HCO_3^-	mg/l	410.7	< 600

Source: created by the authors

Test for increasing the viscosity of a linear gel. Traditionally, polymer systems based on guar are used to give fracturing fluids the necessary rheological properties. Despite their widespread use, such systems have disadvantages associated with changes in viscosity during pumping. An urgent problem is the insufficient viscosity recovery rate after changing the flow regime (from tubing to production string, from the string to perforations) and premature gel destruction. There is a problem of formation contamination with polymer degradation products. This is especially true at high reservoir temperatures in the well. Linear gel is a water-based liquid that is artificially thickened with guar-based chemicals. Guar is a long polymeric chain made up of mannose sucrose and galactose, called polysaccharides. After adding it to water, the viscosity of the liquid increases. Increasing the viscosity is necessary to ensure the effective ability of the linear gel to carry proppant. Table 6 shows the results of the study of four samples to increase the viscosity of a linear gel after adding guar to it.

Table 6. Linear gel test on a blender, Tests 1-4

Value	Test 1	Test 2	Test 3	Test 4
Water temperature, °C	50	49.7	52	53
Water pH level	7.70	7.9	7.9	7.8
Linear gel pH level	8.10	8.1	8.1	8.2
Viscosity, cP	13	13	13	14.5
Hydration time, min	6.5	6.5	6.5	6.5
Viscosity after 2 hours, cP	16.5	16.7	16.5	18

Source: created by the authors

The results of these studies show that this guar gains the required viscosity at these loads and this concentration can be used for subsequent tests. Due to the high temperature and well conditions for which this gel was prepared, it was necessary to increase the viscosity and add a cross-linker to avoid premature propane settling on the bottom hole and producing a stopper.

Linear gel cross-linking test. A cross-linked gel consists of the same materials as a linear gel, but a cross-linking agent is added to increase the viscosity of the linear gel from less than 10 cP to the range of 100 or 1,000 cP. Higher viscosity increases the fracture width so it can accept higher propane concentrations, reduces fluid loss to improve fluid efficiency, improves the fluid's ability to transport propane, and reduces friction pressure. Based on the experience of preparing liquids, if premature formation/disappearance of the funnel occurs or this time does not last longer than 40 seconds, the experiment should be carried out with other concentrations, as the gel will not be stable. The test was conducted according to the methodology described in the relevant section (Table 7). The cross-linking time of the fracturing fluid is an important element in the pumping process, as the cross-linking time must be shorter than the time it takes for the fluid to travel from the surface to the formation.

Table 7. Linear gel test on a blender, Tests 1-4

Value	Test 1	Test 2	Test 3	Test 4
Formation/disappearance of the funnel/cross-linking time, s	12/15/1.15	25/30/3.30	20/25/3.15	15/20/1.50
Cross-linked gel temperature, °C	40	40.5	42	40
Cross-linked gel pH level	8.41	8.49	8.42	8.45

Source: created by the authors

Cross-linked gel shear test. This test is carried out to determine the stability of the system under shear loads during the pumping process. Namely, the gel flows out of the tubing into the production string and passes through the perforations into the formation. The fluid shear stress is equal to the force of resistance on the plates divided by the area of the plates and has units of voltage or pressure (e.g. psi). The shear rate (or velocity gradient) is the relative velocity of the two plates divided by the distance between the plates.

The Brookfield rheometer used in the study is designed for measurements under elevated pressure and temperature conditions and is used for quality control and management in rheological testing. The rheometer is designed to measure the viscosity of liquid Newtonian media, as well as to construct and record rheological curves of non-Newtonian media at high pressures and temperatures. After the shear test, the fluid should have a low shear sensitivity. The time to restore the gel viscosity to 400 cP, after reducing the shear rate, should not be: the beginning of viscosity recovery is 5 seconds and the full viscosity recovery is 1 minute. Figure 2 shows the gel flowing from the tubing into the production string (Section 1) and the gel entering the fracture through the perforations (Section 2).

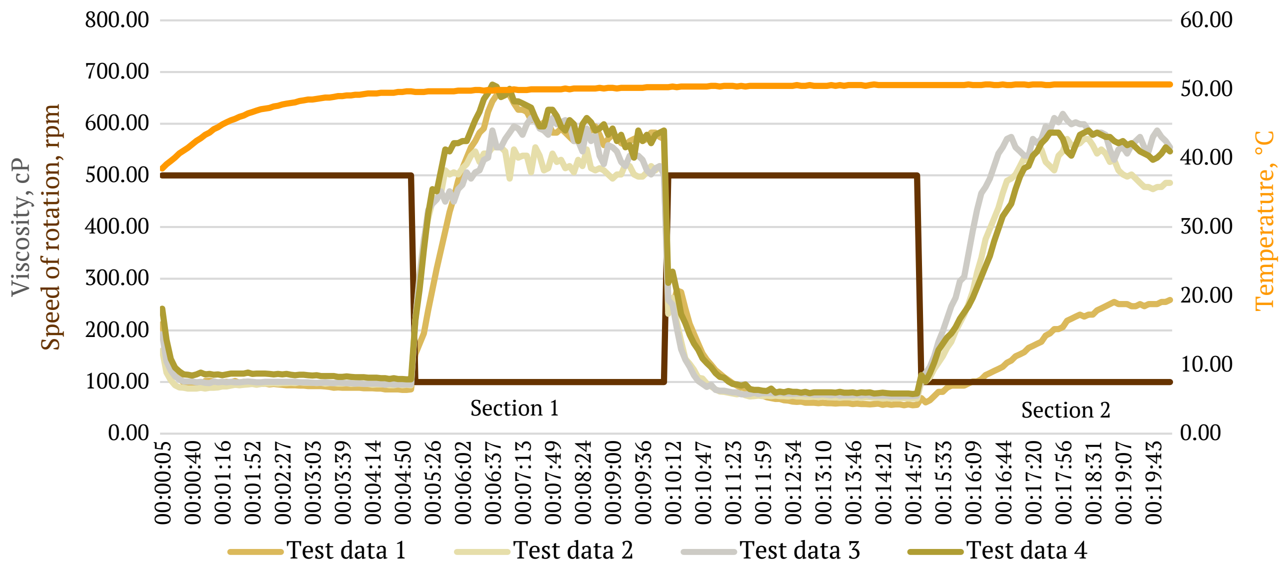

Figure 2. Cross-linked gel shear tests

Source: created by the authors

The first experiment showed a negative result, as the gel did not regain its rheological properties after changing the speed at section 2 (Test 1).

After the addition of the salt stabiliser, the system began to restore its characteristics and gained the required viscosity (Test 2, 3, 4). Since Test 3 is the best at restoring its characteristics, a gel stability study was conducted with this formulation.

Cross-linked gel stability test. The cross-linked gel stability test is performed to ensure that the system will behave consistently and not lose viscosity during the pumping process. During hydraulic fracturing, the viscosity of the fluid should not drop below 400 cP, as this is the minimum viscosity of the fracturing fluid that can hold the proppant in suspension. The results of the test are shown in Figure 3. The values obtained before installation on the rheometer are shown in Table 8.

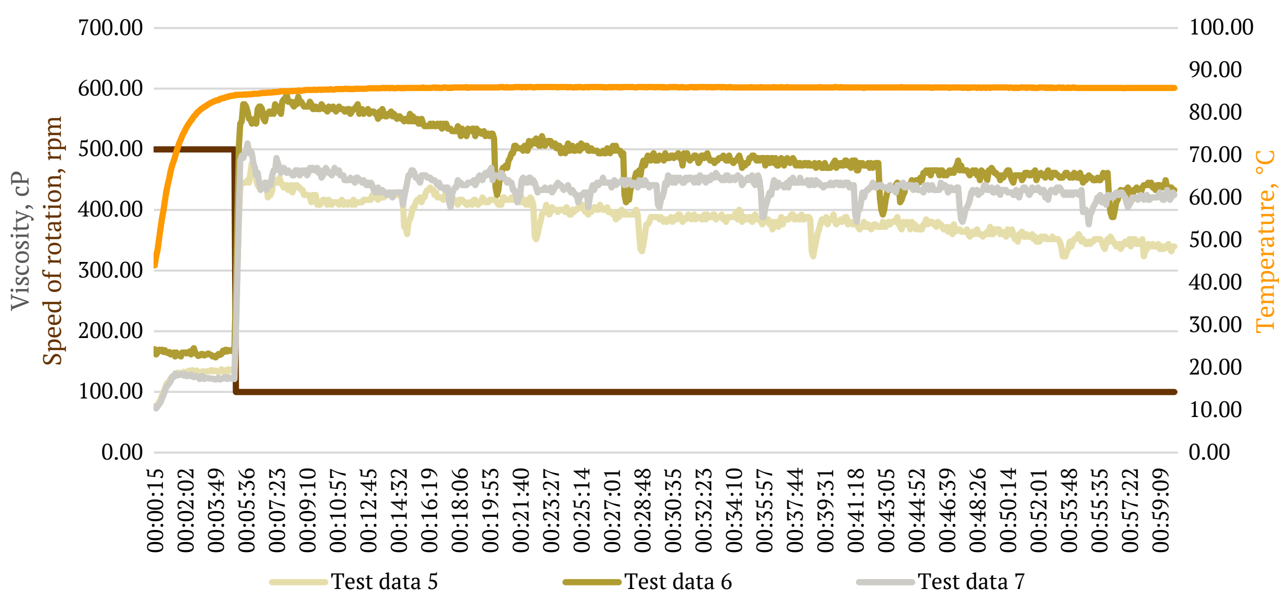

Figure 3. Cross-linked gel stability tests

Source: created by the authors

Table 8. Blender test, Tests 5-7

Value	Test 5	Test 6	Test 7
Water temperature, °C	53.4	52.2	54
Water pH level	7.70	7.8	7.78
Linear gel pH level	8.08	8.1	8.2
Viscosity, cP	13	15	13
Hydration time, min	6.5	6.5	6.5
Time of cross-linking/formation/disappearance of the funnel, s	17/19/2	17/22/1.40	17/20/2
Cross-linked gel temperature, °C	43	42	43
Cross-linked gel pH level	8.40	8.4	8.4

Source: created by the authors

From this graph, it can be concluded that these systems behave stably over time in the range of 350-600 cP, while Test 5 showed that a low concentration of guar leads to a drop in viscosity of 100 cP. Increasing the guar content in Test 6 results in an increase in viscosity at the beginning, but a decrease in viscosity over time of 150 cP. In Test 7, a smaller drop in viscosity (only 50 cP) was achieved with a lower concentration of guar, by increasing the salt stabiliser from 0.5 to 0.6 kg/m^3 and the concentration of slow crosslinker from 2.2 l/m^3 to 2.5 l/m^3. These systems are stable, so the following destruction tests are carried out.

Destruction test of cross-linked gel. This test is an important stage in the process of preparing for hydraulic fracturing, making sure that the gel will break down after the work is completed and will not remain in a viscous form in the formation.

There are slow-acting (encapsulated) and fast-acting (live) destructors. The active ingredient is ammonium persulfate. Often it is necessary to carry out a combination of fast and slow action to achieve the desired result. Table 9 shows the parameters of Tests 8-10 on the blender.

Table 9. Blender test, Tests 8-10

Value	Test 8	Test 9	Test 10
Water temperature, °C	42	45	46
Water pH level	7.90	7.96	7.92
Linear gel pH level	8.04	8.16	8.11
Viscosity, cP	13.5	13	13
Hydration time, min	6.5	6.5	6.5
Time of cross-linking/formation/disappearance of the funnel, s	16/18/1.40	12/15/1.30	17/20/2
Cross-linked gel temperature, °C	37	40	43
Cross-linked gel pH level	8.30	8.32	8.3

Source: created by the authors

Figure 4 shows that the time for complete gel degradation is 20 min, 30 min and 1 hour and 20 min (Tests 8-10). Depending on the amount of proppant per 1 m^3 and the pumping volume, the time required to ensure that the gel does not prematurely break down during the pumping process is set to a value that is sufficient. Also, after the gel is pumped into the formation, it is necessary for it to immediately begin to degrade.

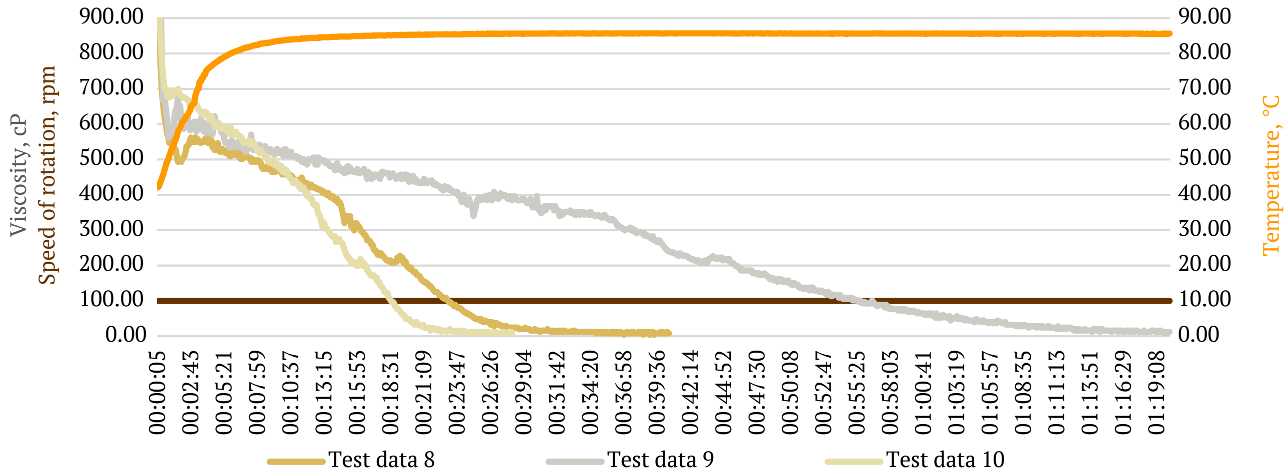

Figure 4. Performing a destruction test on a rheometer

Source: created by the authors

In Table 9, with a guar loading of 2.8 kg/m^3 and the addition of a live breaker of 0.035 kg/m^3 in Test 8, a small amount of pumping can be performed. For larger pumping volumes, it will be necessary to increase the guar concentration to 3.0 kg/m^3 according to Test 9 and reduce the live breaker concentration. A high content of live breaker (Test 10) reduces the pumping time and the risk of premature degradation. Fluid control is the most critical aspect of hydraulic fracturing and must be carried out continuously. For these reasons, fluid tests are carried out not only in the stationary laboratories of contractors, but also directly at the well, in the field laboratory. If the water has passed all the criteria, a polymer and other chemicals are added to it, reagents are used to produce a linear gel, and a bacteria test is carried out, as there are cases when water in wells becomes unsuitable for gel formation. The linear gel sample should not lose viscosity by more than 2 cP/hour. If this drop is recorded, it is necessary to determine from which container the water for this sample was taken and replace it with a new one. Fluid quality control continues during operation. A sample of the linear and cross-linked gel is taken from each stage, the viscosity and cross-linking time must be without deviations, in case of deviations during fluid pumping, it is necessary to re-inject the fluid into the formation, stop, find the cause and repeat the stimulation work. The fluid was required to have a viscosity above 450 cP, not to drop during the pumping period, and to restore its viscosity to this value after shear stress. A well-chosen formulation of chemicals ensured a stable viscosity. Thus, formulations using chemicals from Tests 8-10 can be successfully used for hydraulic fracturing planning.

Discussion

The fracturing fluid must meet the following requirements: compatibility with the formation and formation fluid; minimum friction values; gain of the required viscosity and maintenance of the viscosity index during all stages of hydraulic fracturing; low percentage of filtration into the formation; maximum decomposition of reagents after hydraulic fracturing with minimal formation colmatation; sufficient economic efficiency; ability to transport the unclogging agent into the depth of the fracture; ability to create the required fracture width; possibility of rapid fluid extraction after fracturing and destruction (destruction) of the gel; in the case of clays, preventing their swelling; possibility of preventing re-crosslinking after destruction (Moroz *et al*., 2021). The study was aimed at analysing the chemical composition and effectiveness of hydraulic fracturing fluids, in particular, the impact of polymer systems, cross-linking agents, biocides, and other components. The obtained results indicate the importance of optimising the fluid composition to increase the efficiency of hydraulic fracturing, which correlates with the data of current research in this area.

By analysing the effect of guar concentration on the viscosity of the linear gel, it was found that an increase in guar concentration increases the viscosity of the gel, which in turn provides more efficient transportation of proppant. These results are confirmed by the research of J. Song *et al*. (2020), which also highlights the importance of accurate polymer dosing to achieve optimal rheological properties of the liquid. The author's observations on the rate of recovery of gel viscosity after changing the flow regime partially contrast with the conclusions of the study by A.N. El-hoshoudy *et al*. (2020), which indicates a less significant effect of guar concentration on the rate of viscosity reduction. This may be due to differences in testing methodologies and the characteristics of the water samples used.

The addition of a salt stabiliser was found to be effective in improving the stability of the gel at high temperatures, consistent with the work of H. Khan *et al*. (2021). This underscores the importance of an integrated approach to formulating the chemical composition of fracturing fluid. Also interesting is the opinion of researchers X. Cao *et al*. (2021), who conducted a comparative study of hydraulic fracturing fluids for high-temperature formations with a high salt content, synthetic polymer-based fluids with liquids derived from guar gum. They found that guar gum-based fluids exhibited better shear and temperature resistance, as well as the ability to carry proppant in such challenging conditions. However, the presence of solid residues after the destruction of the gel of guar gum liquids prevents their use in the oil industry. The study shows the prospects of polymer-based synthetic fluids with improved rheological characteristics as an alternative to guar gum systems.

Another aspect of the study involved the analysis of cross-linked gel destruction. It has been established that the use of a combination of fast-acting and slow destructors allows achieving controlled gel disintegration that meets the requirements of efficient hydraulic fracturing. These results are consistent with data from the study by Z. Qu *et al*. (2021), which also demonstrates the importance of choosing the type and concentration of destructors to optimise the gel degradation process. In this study and in the study by W. Kang *et al*. (2020) it is shown that in addition to the main reagents that are present in the hydraulic fracturing fluid contains stabilisers, friction reducers and surfactants, which makes it resistant to high temperatures, improves penetration into the pores of the reservoir, prevents the formation of stable emulsions, minimises capillary effects, protects against corrosion and deposits. These properties make the gel a more efficient and versatile tool for working with oil and gas reservoirs.

An important contribution of this study is the emphasis on the need for an individual approach to each well, taking into account its unique conditions, which is also noted in the paper by T. Jatykov & K. Bimuratkyzy (2022), which considers the problem of optimising the composition of hydraulic fracturing fluids in high-temperature oil and gas fields on the example of the Jurassic oil and gas fields located in the west of Kazakhstan. The study conducted a series of laboratory tests to select appropriate chemicals based on scientific and practical approaches. Tests included checking the thermal stability of the fluid, shear and stability tests. Additionally, emulsion breakdown tests, water analysis, cross-linking time, pH measurements and gel tests were performed. Based on these tests, gelling agents, cross-linkers, breakers and various additives such as demulsifiers, pH buffers, clay inhibitors and biocides were selected. Each component had its own chemical equivalent with the desired concentration. The developed fracturing fluid was successfully used in a 20-tonne fracturing operation in Jurassic sandstones with bottomhole temperatures of up to 105°C and permeability of about 3 mD. The operation was successful and resulted in increased production and encouraging long-term effects. Comparing the results with the presented study, the authors agree with the conclusions of T. Jatykov & K. Bimuratkyzy (2022) who said that the choice of hydraulic fracturing fluid composition at high temperatures requires a careful approach and the use of specialised laboratory tests. Adapting the composition of chemicals to the specific conditions of the field can significantly improve fracturing results and increase well productivity. This confirms that, despite the general trends and recommendations, each fracking case requires a detailed analysis and may differ in terms of the optimal fluid composition.

P. Sharma & V.K. Kudapa (2021) found a decrease in cross-linking time with an increase in the concentration of cross-linking agents. These studies were conducted with a different purpose of creating a fluid to block water in the oil wellbore, but the methodology for creating the gel correlates with the findings of this study. Research by G.G. Vargas *et al*. (2020) focused on the rheological characteristics of a cross-linked water-based guar gum gel. It was found that the gel behaves like a viscoelastic liquid and is slippery even on rough surfaces. This characteristic is important for the fracturing process because it facilitates the movement of the gel along the wall. Particular attention was paid to the maximum stress above which the gel slips, indicating its practical significance for estimating the total pressure drop during hydraulic fracturing. These studies are relevant and it is necessary to conduct additional tests of the rheological properties of the resulting formulation in future studies.

Some studies, like the one by X. Cao *et al*. (2021), focused on optimising water-based gel formulations for hydraulic fracturing to ensure efficient crack formation while minimising environmental impact and reservoir damage. For example, the development of high-temperature resistant, clean and environmentally friendly fracturing fluid systems aims to address reservoirs with conditions that rapidly degrade conventional fracturing fluids. Systems have been developed to maintain efficient rheological properties and stability at extreme temperatures, providing better fracture formation and proppant transport in tight sandstone formations. In the same study, similar results were obtained, but the method of achieving the result was different.

The study proved that with a lower guar content, the required viscosity can be maintained, which in turn will lead to a reduction in formation contamination after gel breakdown. Therefore, the found formulations, namely the number of chemicals in Tests 8-10, can be used to create a hydraulic fracturing design. The next step is to perform hydraulic fracturing and analyse the impact of this formulation on the formation and production after hydraulic fracturing. The discussion not only analysed the results in detail in the context of current research, but also emphasised the importance of an individual approach to each case of hydraulic fracturing, identifying ways to further improve the technology. Based on the comparative analysis, it can be concluded that the authors' research makes a significant contribution to understanding the interaction of chemical components in hydraulic fracturing fluids and their impact on process efficiency. However, the identified differences indicate the need for further detailed research to develop optimal liquid formulations, taking into account a variety of reagents.

Conclusions

A comprehensive study was carried out to analyse the main requirements for fracturing fluids and optimise their formulations for use at a formation temperature of 85°C. This work contributes to a deeper understanding of the importance of selecting appropriate chemical components and their concentrations to improve the efficiency of the fracturing process. The aim set at the beginning of the study was achieved. Particular attention was paid to optimising the fracturing fluid formulation, which would not only achieve the required viscosity and rheological properties but also ensure their stability during the operation. The results of the study showed that the selection of water compatible with chemicals is critical to the preparation of an effective fracturing fluid. Testing of different types of guars has shown that choosing a higher quality guar allows you to achieve the desired viscosity at lower concentrations, which has a lower impact in terms of degradation products. Experiments aimed at analysing the rheological characteristics of cross-linked gels under shear loads confirmed the ability of three specific concentrations to restore the required viscosity above 450 cP.

Further study of the stability of these gels showed that the two selected formulations effectively retained their properties for one hour without reducing their viscosity to below 450 cP. The study and destruction of the cross-linked gel highlighted the importance of choosing the right concentration of destructors to ensure rapid gel disintegration after the fracturing procedure and faster cleaning of the wellbore, including deeper destruction of the gel without the formation of lumpy clots during its disintegration. These findings highlight the need for detailed monitoring of fracturing fluid parameters not only at the laboratory stage but also during well operations. Further research should focus on the development of new gel and fracturing agent formulations with improved environmental performance and higher stability at extreme temperatures, paving the way for optimisation and increased hydrocarbon recovery after hydraulic fracturing.

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Conflict of Interest

None.

References

[1] Al-Hajri, S., Negash, B.M., Rahman, M.M., Haroun, M., & Al-Shami, T.M. (2022). Perspective review of polymers as additives in water-based fracturing fluids. *ACS Omega*, 7(9), 7431-7443. doi: 10.1021/acsomega.1c06739.

[2] Almubarak, T., Ng, J.H.C., AlKhaldi, M., Panda, S., & Nasr-El-Din, H.A. (2020). Insights on potential formation damage mechanisms associated with the use of gel breakers in hydraulic fracturing. *Polymers*, 12(11), article number 2722. doi: 10.3390/polym12112722.

[3] API RP 39: Recommended practices on measuring the viscous properties of a cross-linked water-based fracturing fluid. (1998). Retrieved from https://standards.globalspec.com/std/997097/api-rp-39.

[4] API RP 45: Recommended practice for analysis of oilfield waters. (1998). Retrieved from https://standards.globalspec.com/std/1647351/api-rp-45.

[5] Cao, X., Shi, Y., Li, W., Zeng, P., Zheng, Z., Feng, Y., & Yin, H. (2021). Comparative studies on hydraulic fracturing fluids for high-temperature and high-salt oil reservoirs: Synthetic polymer versus guar gum. *ACS Omega*, 6(39), 25421-25429. doi: 10.1021/acsomega.1c03394.

[6] El-hoshoudy, A.N., Zaki, E.G., & El-Saeed, S.M. (2020). Experimental and Monte Carlo simulation of palmitate-guar gum derivative as a novel flooding agent in the underground reservoir. *Journal of Molecular Liquids*, 302, article number 112502. doi: 10.1016/j.molliq.2020.112502.

[7] Huang, Y., Yao, X., Dai, C., Wu, Y., Li, L., & Yuan, B. (2024). A supramolecular reinforced gel fracturing fluid with low permeability damage applied in deep reservoir hydraulic fracturing. *Gels*, 10(1), article number 2. doi: 10.3390/gels10010002.

[8] Jatykov, T., & Bimuratkyzy, K. (2022). A chemical design example of hydraulic fracturing fluids in high-temperature hydrocarbon reservoirs: Case study. *Trends in Sciences*, 19(12), article number 4610. doi: 10.48048/tis.2022.4610.

[9] Kang, W., Mushi, S.J., Yang, H., Wang, P., & Hou, X. (2020). Development of smart viscoelastic surfactants and its applications in fracturing fluid: A review. *Journal of Petroleum Science and Engineering*, 190, article number 107107. doi: 10.1016/j.petrol.2020.107107.

[10] Khan, H., Spielman-Sun, E., Jew, A., Bargar, J., Kovscek, A., & Druhan, J. (2021). A critical review of the physicochemical impacts of water chemistry on shale in hydraulic fracturing systems. *Environmental Science & Technology*, 55(3), 1377-1394. doi: 10.1021/acs.est.0c04901.

[11] Liu, S., Huang, J., Tang, S., Shi, S., Wu, X., & Liu, X. (2020). Experimental study on the damage of artificial fracture permeability in coal during the flow back of guar-based fracturing fluid. *Geofluids*, 2020, article number 8302310. doi: 10.1155/2020/8302310.

[12] Montgomery, C. (2013). Fracturing fluids. In A.P. Bunger, J. McLennan & R. Jeffrey (Eds.), *Effective and sustainable hydraulic fracturing* (ch. 1). London: IntechOpen. doi: 10.5772/56192.

[13] Moroz, L., Uhrynovskyi, A., & Kogut, G. (2023). Investigation of the effect of polymer concentration in fracturing fluid on crack size and permeability during hydraulic fracturing. *Archives of Materials Science and Engineering*, 122(2), 70-77. doi: 10.5604/01.3001.0053.9594.

[14] Moroz, L., Uhrynovskyi, A., & Popovych, N. (2021). Study of hydraulic fracturing at oil wells to intensify production. *InterConf*, 87, 332-337. doi: 10.51582/interconf.21-22.11.2021.040.

[15] Qu, Z., Wang, J., Guo, T., Shen, L., Liao, H., Liu, X., Fan, J., & Hao, T. (2021). Optimization on fracturing fluid flowback model after hydraulic fracturing in oil well. *Journal of Petroleum Science and Engineering*, 204, article number 108703. doi: 10.1016/j.petrol.2021.108703.

[16] Quainoo, A.K., Bavoh, C.B., & Negash, B.M. (2022). Rheological and viscoelastic property characterizations of amino acid-based hydraulic fracturing fluids. *Energy & Fuels*, 36(7), 3539-3548. doi: 10.1021/acs.energyfuels.1c04396.

[17] Sharma, P., & Kudapa, V.K. (2021). Study on the effect of cross-linked gel polymer on water shutoff in oil wellbores. *Materials Today: Proceedings*, 48(5), 1103-1106. doi: 10.1016/j.matpr.2021.07.506.

[18] Song, J., Navarrete, R., Asadi, M., & Jin, B. (2020). New high viscosity friction reducers for proppant transport in hydraulic fracturing. In *SPE international conference and exhibition on formation damage control* (article number SPE-199330-MS). Lafayette: Society of Petroleum Engineers. doi: 10.2118/199330-ms.

[19] Vargas, G.G., Andrade, R.M., Loureiro, B.V., & Soares, E.J. (2020). Rheological properties of a cross-linked gel based on guar gum for hydraulic fracture of oil wells. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 42, article number 498. doi: 10.1007/s40430-020-02579-w.

[20] Wang, J., Guo, P., Jiang, H., & Zhou, F. (2022a). A novel multifunction fracturing fluid compounding of nano-emulsion and viscous slickwater for unconventional gas and oil. *Arabian Journal of Chemistry*, 15(5), article number 103749. doi: 10.1016/J.ARABJC.2022.103749.

[21] Wang, M., Cheng, H., Wei, J., Zhang, K., Cadasse, D., & Qin, Q. (2022b). High-temperature-resistant, clean, and environmental-friendly fracturing fluid system and performance evaluation of tight sandstone. *Journal of Environmental and Public Health*, 2022, article number 5833491. doi: 10.1155/2022/5833491.

[22] Xu, H., Zhou, F., Li, Y., Su, H., Yang, S., Yao, E., & Zhu, Y. (2023). Preparation and properties evaluation of novel silica gel-based fracturing fluid with temperature tolerance and salt resistance for geoenergy development. *Arabian Journal of Chemistry*, 16(12), article number 105324. doi: 10.1016/j.arabjc.2023.105324.

[23] Zhao, M., Li, Y., Xu, Z., Wang, K., Gao, M., Lv, W., & Dai, C. (2020). Dynamic cross-linking mechanism of acid gel fracturing fluid. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 607, article number 125471. doi: 10.1016/j.colsurfa.2020.125471.

Удосконалення рецептури рідини гідророзриву

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Анотація. Зростаюча потреба в нарощуванні видобутку природніх вуглеводнів робить технологію гідравлічного розриву пласта одним із ключових методів інтенсифікації видобутку, тому актуальним питанням стає необхідність підвищення ефективності та економічності гідророзриву, що може бути досягнуто за рахунок оптимізації складу рідини. Мета дослідження полягала в пошуку ефективних рецептур технологічної рідини для гідравлічного розриву пласта, які б мали структурно-реологічні властивості необхідні для успішного проведення гідророзриву у свердловинах із температурою більше 80 °C. Використано емпіричну методику проведення лабораторних досліджень рецептур рідин гідророзриву. Для обґрунтування реологічних властивостей рідин для гідравлічного розриву пласта було проведено їх тестування. Цей метод передбачав систематичне тестування різних комбінацій компонентів рідини з метою підбору оптимального складу, який би відповідав вимогам ефективного та економічного гідророзриву за підвищеної температури свердловин. Проаналізовано основні види рідин гідророзриву і їх рецептури, наведено результати лабораторних досліджень із підбору оптимальних параметрів рідини гідророзриву у свердловині з пластовою температурою 85 °C. Експериментально встановлено взаємозв'язок між хімічним складом (рецептурою) рідини для гідророзриву і її реологічними властивостями за температури 85 °C. Методом підбору рецептур знайдено склад рідини гідророзриву, яка витримує зсувові навантаження, стабільна та не руйнується передчасно. Запропоновано рецептуру рідини, яку можна використати під час проведення гідравлічного розриву пласта на газових і нафтових родовищах. Практична реалізація результатів дослідження дозволить підвищити ефективність технології гідророзриву пласта й збільшити продуктивність нафтових і газових свердловин

Ключові слова: привибійна зона пласта; свердловина; гідравлічний розрив пласта; лінійний гель; лабораторні тести рідини; полімери