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Experimental Study of the Hydraulic Fracture Formation and Propagation

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Abstract

Hydraulic fracturing is the primary method of intensifying the oil flow to the well. Despite the long history of this method's application and the variety of software aimed at hydraulic fracturing design, oil-producing and oil service companies often face problems during hydraulic fracturing, some of which are associated with insufficient elaboration of physical models used in software packages. Sadovsky Institute of Geosphere Dynamics of Russian Academy of Sciences has developed and constructed a unique installation that allows conducting hydraulic fracturing experiments on samples of artificial porous material selected in accordance with similarity criteria. The samples have the shape of disks with a diameter of 430 mm and a height of 70 mm. The installation allows loading samples along three independent axes, creating pore pressure gradients, measuring the fluid pore pressure at several points, registering acoustic emission, probing the sample with acoustic pulses. The article discusses the results of experiments conducted at this installation, shows the need to advance the models used to describe the process of formation and propagation of hydraulic fractures in a permeable formation in a complex stress state. The results of experiments on the study of the hydraulic fracture interactions with discontinuity created in advance in the model sample are also presented.

Keywords: Hydraulic fracturing; Laboratory modelling; Porous media; Stress-strain state; Breakdown pressure

1. INTRODUCTION

Along with water injection to maintain reservoir pressure, hydraulic fracturing is the main method of stimulating oil and gas production. The hydraulic fracturing is the creation of a tensile fracture in the rock by pumping fluid under high pressure into a certain interval of the well. There are various both theoretical and experimental studies of the formation and growth of hydraulic fractures [1–7]. Theoretical models have limitations of their applicability. Model parameters can only be determined and verified experimentally. It is impossible or complicated to conduct experiments under real conditions of the developed hydrocarbon fields, therefore, experiments are usually carried out in laboratories on samples of real rocks or on artificial samples. In case of choosing the material of the artificial samples, it is necessary to use similarity criteria to ensure the applicability of the experimental results to real situations. Similarity criteria are proposed in the works [8,9] on the basis of equations that determine the hydrodynamics and geomechanics of fracture formation.

Laboratory modeling of hydraulic fracturing in various settings are numerous. The notable breakthrough in this direction has been achieved by Schlumberger [10], whose equipment allows conducting experiments on samples measuring 76×76×91 cm in reservoir conditions. Nevertheless, work on installations using large real rock samples has a number of disadvantages: the complexity and high cost of preparing and conducting experiments, the remaining questions about the reliability of transferring the results obtained on samples, although

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large, but still small compared to real situations, the heterogeneity of the stress field due to the shape of the samples, the difficulty of obtaining homogeneous samples of large size, etc. Similar installations, but with significantly smaller sample sizes (usually about 30×30×30 cm), are available in a number of leading geomechanical laboratories in the world (for example, at Delft University, the Netherlands). An overview of the installation options is presented in Ref. [10]. Meaningful results of investigation on the interaction of hydraulic fractures with natural cracks are presented in Ref. [11]. Fracture interaction during multistage fracturing in horizontal wells was considered theoretically [12]. Recently, there has been an increased interest in the problem of interaction between fractures and neighboring wells. It is also essential to understand how changes in pore pressure in the formation can affect the propagation of a hydraulic fractures.

There are three approaches to hydraulic fracturing modeling:

- study of small samples of real rocks;
- selection of materials and experimental conditions in accordance with similarity criteria;
- creation of simplified laboratory models corresponding to theoretical approximations.

The description of the first two approaches is given in a number of publications. The efficiency of simplified experiments conducted under theoretical model conditions is not so obvious, but such experiments allow solving some numerical problems.

The materials used in the experiments can also be divided into three groups:

1. Homogeneous materials using natural samples, gelatins, gypsum, cement, polymethylmethacrylate [13].
2. Anisotropic materials using natural samples, gelatins, gypsum, cements [14].
3. Samples with special discontinuities, cracks, unequal stress field, different angles of the well relative to the main stress axes [15].

The sample sizes range from centimeter-scale cylinders at hydrostatic and triaxial stresses to meter-scale blocks at true triaxial stresses.

This article provides an overview of the results of experiments conducted using a unique hydraulic fracturing modeling facility at the Sadovsky Institute of Geosphere Dynamics of the Russian Academy of Sciences. The purpose of these experiments was to investigate the possibility of the influence of changes in the stress state of the rock on the direction of the fractures and the formation of new ones, and to obtain estimates of the growth rate of the fractures and the rate of filling the fracture with fluid. Comparison of the experimental results with the theoretical estimations using standard methods showed the need to refine the models used considering the diffusion of fluid pressure and the plastic properties of reservoir rocks.

2. EXPERIMENTAL SETUP AND MEASUREMENT METHODS

The installation used differs from analogues in its shape and size [16]. Structurally, the installation consists of two disks and a side ring (Fig. 1). The thickness of the discs is 75 mm with an outer diameter of 600 mm. The height of the side ring is 75 mm with an internal diameter of 430 mm and thickness of 25 mm. The dimensions of the high-pressure chamber are 430 mm in diameter and 66 mm in height.

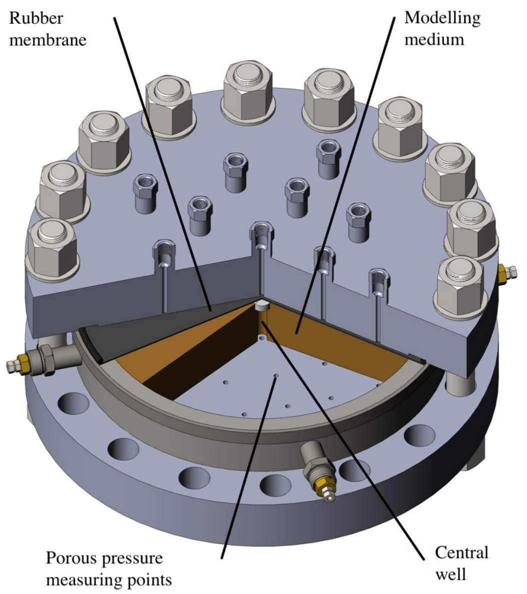
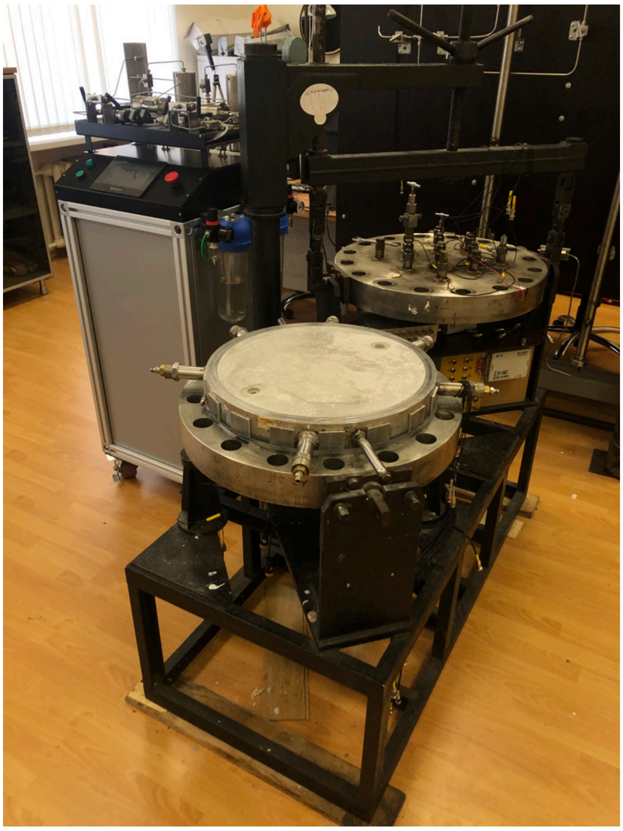


Fig. 1. Diagram of the hydraulic fracturing simulation setup.

The upper disk is separated from the sample by a rubber membrane. The space between the disk and the membrane is filled with water under pressure, which allows one to set a vertical load on the sample. Horizontal loading of the sample is carried out using chambers located on the inner surface of the side ring. The chambers are made of 0.3 mm thick copper sheet. The inner hollow of the chambers has a thickness of 3 mm, the height of the chamber is 2 mm less than the height of the side ring. The length of the chamber arc is approximately 80°. Lateral (side) loading is carried out by pumping fluid into opposite chambers in pairs. Photos of the installation are shown in Fig. 2.

The holes with a diameter of 6 mm are drilled in both discs and in the side ring. There are 29 holes in the lower disk, 13 in the upper one, and 6 in the sidewall. These holes are designed both for mounting various sensors, and



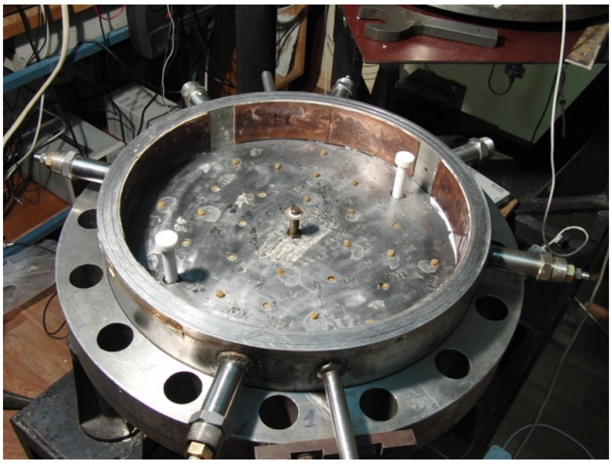


Fig. 2. Photos of the hydraulic fracturing simulation setup. On the inside surface of the side ring, chambers for creating horizontal stresses are visible; in the center there is a model well for hydraulic fracturing; on the sides there are auxiliary wells for creating a pore pressure gradient.

for providing fluid pumping out or injection into the sample. Piezoelectric acoustic emission transducers are mounted directly into the inner surface of the discs. The layout of the sensor positions is shown in Fig. 3. The tested samples of artificial porous materials have the shape of disks. The installation allows to create an unequal stress state, set pore pressure gradients, conduct hydraulic fracturing under conditions of constant fluid flow rate or constant fluid pressure, measure pore pressure and acoustic emission.

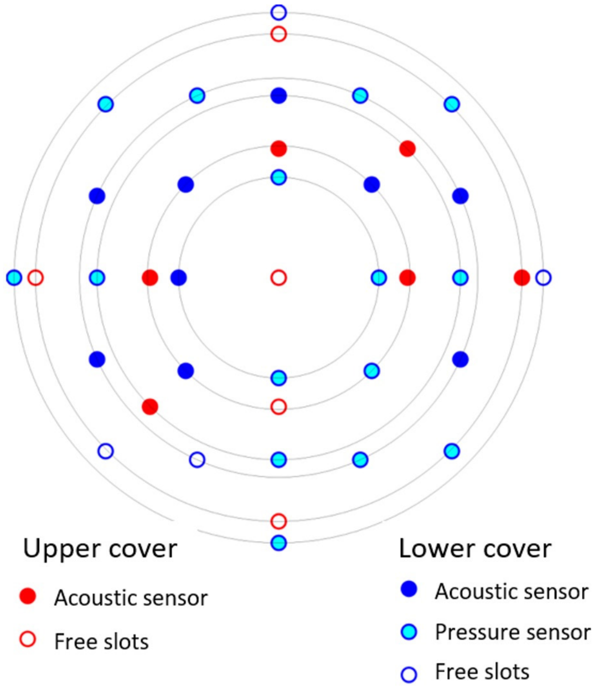


Fig. 3. Layout of pressure sensors and acoustic emission sensors in a top view of the setup.

Created loads:
- vertical stress up to 120 atm;
- lateral stress up to 80 atm;
- difference in the horizontal stresses up to 80 atm;
- porous pressure up to 100 atm.

Fluid injection parameters:
- at constant pressure (up to 100 atm);
- at constant rate;
- at constant pressure drop (up to 80 atm between the injection and drain points).

Recorded values:
- flow rate and pressure of the fluid injected into the sample;
- pore pressure;
- vertical and horizontal stresses;
- acoustic emission;
- elastic wave travel time.

The choice of the sample material modeling the collector is determined both by similarity criteria and by technological factors of manufacturing experimental samples. A mixture of gypsum and cement in a ratio of 9:1 was used as a model material, 45% water was added to the mixture. To slow down the setting of gypsum, citric acid is added to the water at a concentration of 2 g/dm^3. The good fluidity of the mixture and the absence of shrinkage during solidification allow tight contact with the installation inside. The material properties were determined experimentally and are shown in Table 1. Here E is Young's modulus, ν is Poisson's ratio, UCS is uniaxial compressive strength, $TSTR$ is uniaxial tensile strength, k is permeability, φ is

Table 1. Properties of the sample material.

E, GPa	ν	*UCS*, MPa	*TSTR*, MPa	*k*, m^2	φ, %
3.7	0.2	6.4	0.8	$2.7 \cdot 10^{-15}$	40

porosity. Detailed information about determining the properties of the material used and the assessment of similarity criteria for the experiments carried out can be found in Ref. [17].

The following series of experiments were carried out:

1. A certain pore pressure gradient was created in the sample with the help of auxiliary wells, then a hydraulic fracture was formed by pumping fluid through the central well. The injection stopped, the installation was disassembled and the orientation of the resulting fracture was checked. After that, the installation was assembled again, the pore pressure gradient was changed by pumping fluid through other auxiliary wells. Hydraulic fracturing fluid was pumped again through the central well until the pressure drop, which determined the formation of a new fracture or the propagation of the fracture formed earlier.
2. In another series of experiments, after the formation of the first fracture, the orientation of the main compressive stresses was changed and the possibility of forming a new fracture from the same well was determined.
3. A special series of experiments was conducted to determine the rate of fracture growth and filling it with fluid.
4. Separate experiments were carried out to determine the possibility of hydraulic fracture growth during cyclic injection of fluid under pressure significantly lower than the breakdown pressure.

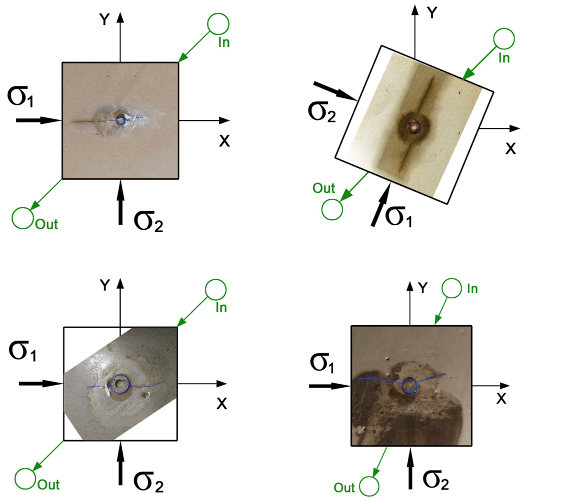


Fig. 4. Orientation of fractures in experiments to determine the influence of pore pressure on the trajectory of fracture propagation. In – an injection well, Out – a production well.

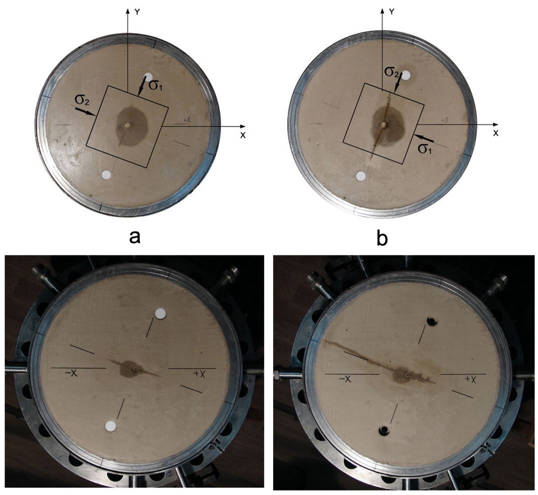


Fig. 5. Experiments to determine the effect of changing the orientation of the principal stress axes on the development of hydraulic fractures.

3. RESULTS

The results of a series of experiments on studying the effect of the orientation of the pore pressure gradient on the trajectory of hydraulic fractures are given below. The experimental conditions are given in Table 2.

Here σ_1 / σ_2 is the ratio of the applied maximum horizontal load to the minimum; *P* is the pressure in the injection well; *D* is the distance from the injection well to the central; α is the angle between the direction of action of the maximum horizontal loads and the line connecting the auxiliary wells.

Table 2. Conditions of the experiments on studying the pore pressure gradient effect.

№	σ_1 / σ_2	*P*, MPa	*D*, m	α, degree
1	1.82	1	0.171	45
2	1.82	2	0.171	22.5
3	1	1	0.171	90
4	1.37	1.5	0.129	66

Examples of fractures formed are shown in Fig. 4. In all experiments, the main direction of fracture propagation corresponds to the direction of the axis of the maximum principal stress, along with this a deviation of the fracture from this axis towards the injection well and from the “producing” well is observed. Experiments have shown that with minor contrasts of horizontal stresses, the pore pressure gradient has a significant effect on the fracture trajectory.

In the second series of experiments after the first stage of hydraulic fracturing, the orientation of fractures also corresponds to the direction of maximum horizontal stresses. The fracture after the first stage is shown in Fig. 5a. After the minimum and maximum horizontal

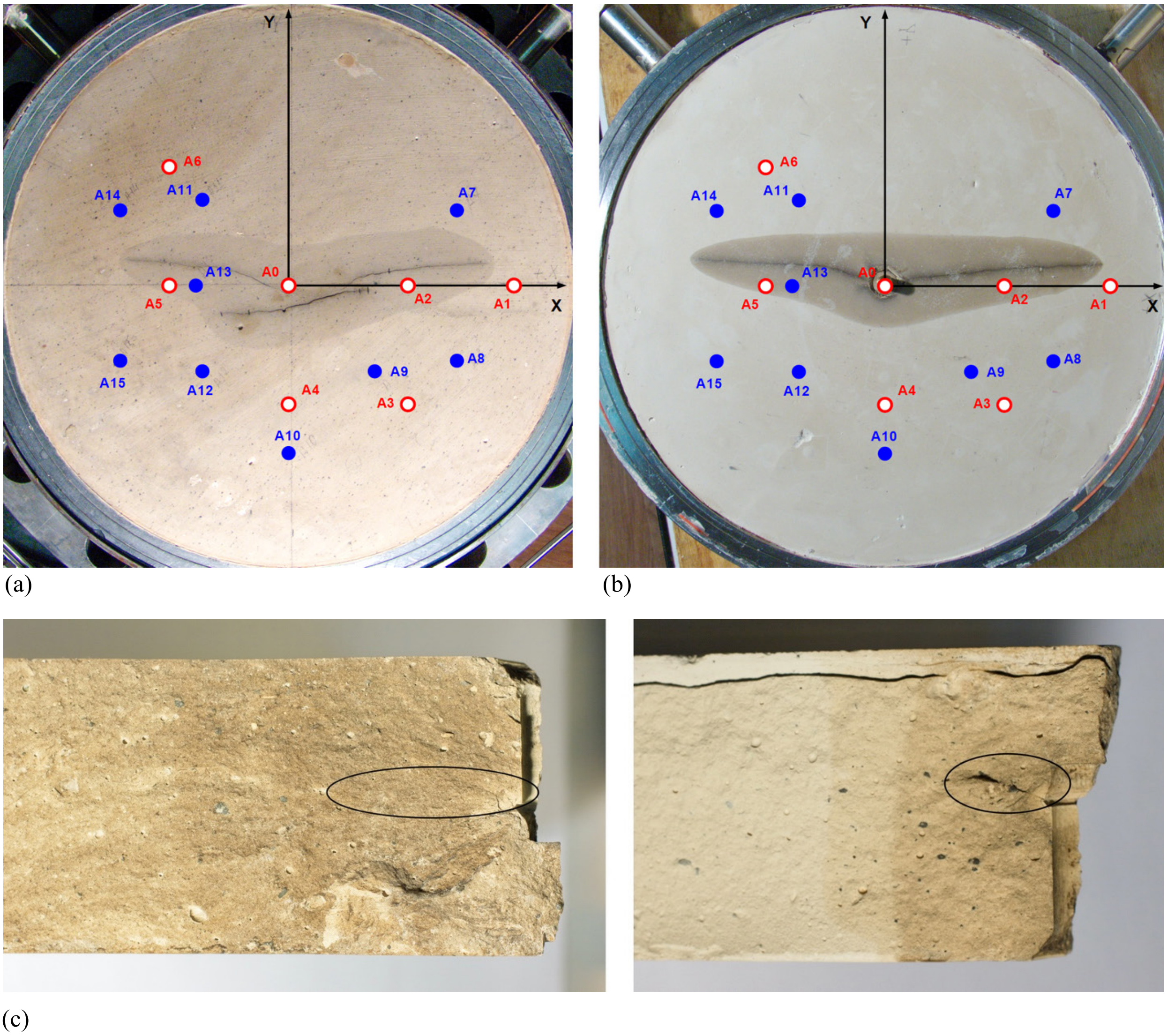


Fig. 6. Photographs of the upper (a) and lower (b) surfaces and the sections of the sample (c) after obtaining a secondary hydraulic fracture.

stresses were reversed, the pumping was performed again. No new fractures have formed, the initial fracture has sprouted, deviating towards the new direction of action of maximum horizontal stresses (Fig. 5b). Note that the fracture reopening pressure was about 30% less than the breakdown pressure.

In the third series of experiments, the maximum load was applied in the horizontal direction, the vertical component of the stresses was less than the horizontal ones $\sigma_V = 1$ MPa, $\sigma_h = 2$ MPa. Thus, the primary fracture was formed in the horizontal plane. After the first fracture was initiated, the values of the applied lateral and vertical loads were changed to the following: $\sigma_V = 1.5$ MPa, $\sigma_h = 0.5$ MPa in order to obtain a vertical fracture. The new fracture actually spread in the vertical plane despite the fact that the perforation was located in the horizontal plane (Fig. 6).

In this series of experiments the formation, development and filling of a hydraulic fracture with fluid was monitored by recording ultrasonic pulses passing through the sample. Acoustic pulses were recorded by piezoelectric transducers located in the lower disk (Fig. 2), piezoelectric transducers located in the upper disk served as emitters. Fig. 7 shows an example of the pressure dependence on time in the central well, synchronized with the dependences of the amplitude of the ultrasonic pulses that passed through the sample during the formation of a horizontal fracture on time. It can be noted that the decrease in the amplitude of the ultrasonic pulses on the receivers begins before the maximum pressure is reached. It indicates the beginning of the hydraulic fracture growth at a pressure less than the maximum. After the decline, the amplitudes rise, which is caused by filling the fracture with a fluid. In contrast to the decline, the beginning of the am-

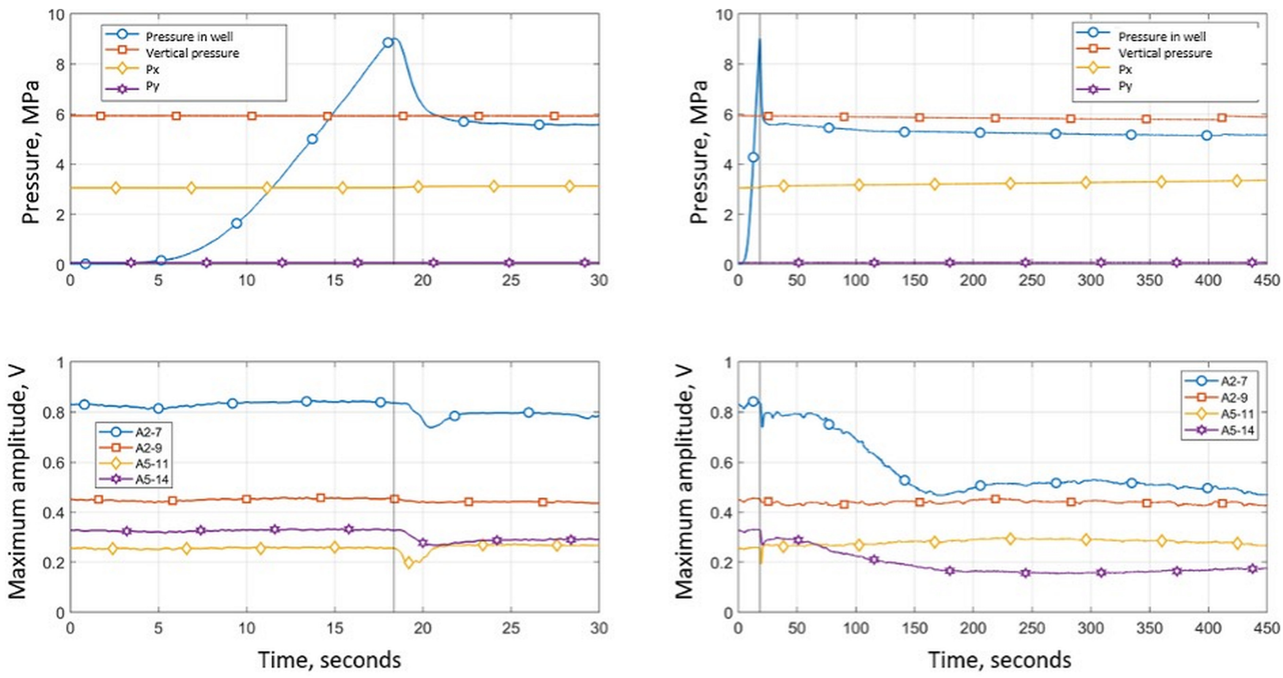


Fig. 7. Initial section (on the left) and complete records (on the right) of the dependences of pressure in the central well and loading pressure on time (upper graphs) and the amplitude of ultrasonic pulses for different receivers (lower graphs).

plitude growth is clearly localized in time. Taking into account the spatial location of the source of ultrasonic pulses, receivers and the geometry of the fracture, it is possible to estimate the propagation velocity of the hydraulic fracturing fluid front, which was ≈35 mm/s, the fracture growth rate is estimated at 100–130 mm/s.

After the rise of the amplitude of the ultrasonic pulses, a significant decrease is recorded, which is apparently due to the increase of the formed fracture aperture. At the receivers located closer to the central well, this decline is maximum. There is more than three-fold drop in amplitude compared to the initial value (before the fracture formation). Then the pulse amplitude stabilizes. When the injection is stopped, the amplitude of the ultrasonic pulses begins to grow, which indicates that the fracture closes as the pressure in it decreases.

A series of experiments was carried out to study the possibility of fracture growth during cyclic injection of fluid with a pressure less than the breakdown pressure. An example of pressure changes in the central well during injection with a constant flow rate is shown in Fig. 8a. The breakdown pressure in this experiment was 5.3 MPa, after reducing the pressure, it was 3.2 MPa. After fixing the formed fracture (Fig. 9a), the experiment continued at the cyclically varying pressure shown in Fig. 8b. The vertical load on the sample was set to 4 MPa, the horizontal loads were 0.1 MPa, the injection pressure did not exceed 2.4 MPa. An example of a fracture resulting from a cyclic change in the injection pressure is shown in Fig. 9b.

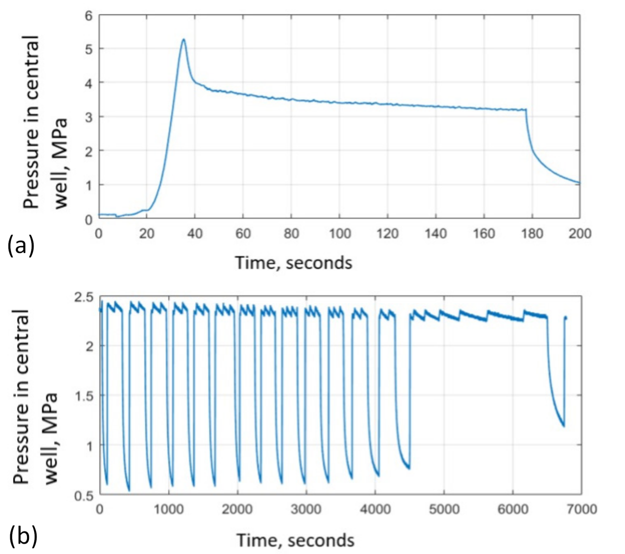


Fig. 8. Pressure change in the central well: (a) the formation of a hydraulic fracture during injection with a constant flow rate; (b) cyclic injection with controlled pressure (lower).

4. DISCUSSION

During the experiments described, attention was drawn to the fact that the pressure of the injected fluid, at which a hydraulic fracture occurs, turned out to be significantly higher than expected according to preliminary estimates. There are several approaches for estimating the breakdown pressure of hydraulic fracturing [18–20]. In this

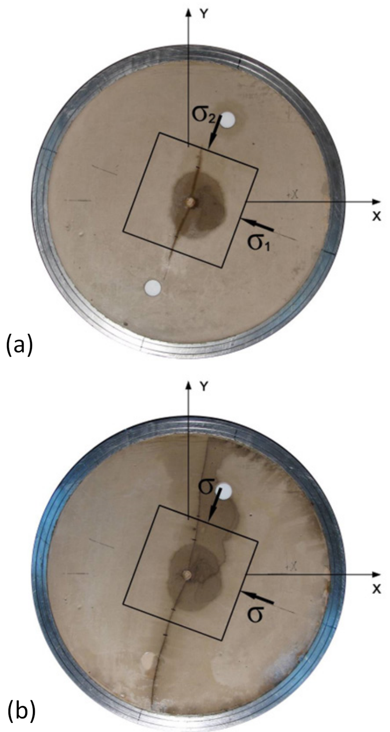


Fig. 9. Photo of the sample: (a) hydraulic fracture after injection at a constant flow rate; (b) fracture after injection with a cyclic change in injection pressure.

study, the work [19] was used to estimate the breakdown pressure, which is determined based on the solution of the classical Kirsch problem of stress concentration around a circular hole [21].

The fracture initiation occurs when the value of the tangential component of the stress on the hole exceeds the uniaxial tensile strength of the rock. The pressure of the injected fluid is called fracture breakdown pressure *FBP*, which can be written as follows:

$$FBP = 3\sigma_h - \sigma_H + UTS.$$

Here σ_h and σ_H are the minimum and maximum horizontal components of the main stresses, *UTS* is the uniaxial tensile strength of the medium. This approach does not take into account the change in the stress state of the near-well area due to fluid filtration and changes in pore pressure, although this leads to an increase in the breakdown pressure. Taking into account the additional compressive stress due to pressure changes in the near-well area, the expression for breakdown pressure (*FBP*) can be rewritten as follows:

$$FBP = 3\sigma_h - \sigma_H + UTS + \sigma_b.$$

Here σ_b denotes the reverse stress (backstress), considered in detail in Refs. [1,18,20,22–24]. To determine the breakdown pressure, it is proposed to calculate the backstress using the formula:

$$\sigma_b = \eta\left(FBP - \sigma_h\right),\ \eta = \frac{\alpha\left(1-2\nu\right)}{2\left(1-\nu\right)},$$

where η is poroelasticity coefficient, α is Biot coefficient and ν is Poisson's ratio. It is shown in Ref. [25] that taking into account the doubled effect of backstress reduces the difference between theoretical and experimental values of breakdown pressures.

When analyzing the experimental results, it was also found that standard methods for determining the minimum principal stresses by the fracture closure pressure give results that differ significantly from the magnitude of the applied load. It was assumed that the detected discrepancy, as in the case of breakdown pressure, was caused by the need to take into account the backstress. A more accurate calculation of the stresses in the sample under applied loads, taking into account the effect of backstress [25], allowed, as in the case of the breakdown pressure, to reduce the difference between the calculated and experimental values of the minimum principal stresses.

The use of methods of ultrasonic sounding of a hydraulic fracture in laboratory experiments allowed us to identify important features of its propagation. In the experiment on the formation of a horizontal hydraulic fracture (perpendicular to the axis of the well), the presence of a lag was confirmed and the average value of the velocity of the fluid front in the fracture was estimated. The magnitude of this velocity (22–35 mm/s) is comparable to the average velocity of the fluid front propagation of 70 mm/s, directly measured in the experiment on the formation of a horizontal fracture in a sample with a diameter of 105 mm, described in Ref. [26].

The results of the performed experiments confirmed the data [11] that the formation of a hydraulic fracture begins before the pressure in the well reaches maximum. As the fracture propagates, its dry tip is formed, the flow of fluid through the fracture at this stage is less than the specified injection fluid flow. As the fracture aperture grows (which manifests itself in a decrease in the amplitude of the passing ultrasonic pulses), the fluid flow into the fracture increases and begins to exceed the injection flow rate; this, together with the elastic expansion of the fluid, leads to a drop in pressure. The advance of the fluid front in the fracture is manifested in an increase in the amplitudes of the ultrasonic pulses, however, the continued expansion of the fracture aperture after some time again leads to a decrease in the amplitude of the passing pulses. After stopping the injection, the fracture begins to close, which increases the amplitude of the pulses.

The experiments carried out confirmed the possibility of forming a new fracture oriented vertically (along the well), in the presence of an initial horizontal fracture in the same well. The secondary fracture was created only as a result of a change in the stress state of the reservoir model. It should be noted that there are no other special measures, such as priming, perforation of the well, aimed at stimulating the formation of a new fracture in a given direction (as was done, for example, in Ref. [5]).

A series of repeated experiments with an increase in the stress component perpendicular to the plane of the primary crack showed a redistribution of fluid flows during the formation of a secondary fracture, which manifested itself in a change in the amplitude variations of the probing ultrasonic pulses.

Experiments on modeling fracture growth with cyclic changes in injection pressure have shown that the growth of the initial stopped fracture can be resumed at a pressure in the well significantly lower than when the hydraulic fracturing operation is terminated. This result is important when planning the switching of the producing well with hydraulic fracturing to the water injection mode to maintain reservoir pressure.

5. CONCLUSIONS

1. The breakdown and closure pressure are not determined by the simplest models, it is necessary to take into account the increase in pressure in the vicinity of the fracture, the plasticity of the rock and the real tensile strength of the rock.
2. Hydraulic fractures formation can be divided into stages:
   - dry fracture tip formation;
   - fracture fulfilling with fluid;
   - fracture opening, fracture growth with an almost constant aperture;
   - fracture closure at the moment next to the injection stop.
3. The fracture occurs before the injection pressure reaches its maximum.
4. The condition for the appearance of a secondary hydraulic fracture depends on a significant change in the orientation of the axes and the magnitude of the main stresses.
5. The propagation of hydraulic fractures is possible at pressures significantly lower than the breakdown pressure.

It was found that with a smaller stress contrast, the pore pressure field has a greater influence on the direction of fracture propagation. The possibility of creating a repeated hydraulic fracture by changing only the stress-strain state without additional actions, such as, for example, plugging of an old perforation or the entire fracture, has been experimentally confirmed.

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Экспериментальное исследование образования и развития трещин гидроразрыва пласта

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Аннотация. Гидравлический разрыв пласта (ГРП) является основным методом увеличения притока нефти к скважине. Несмотря на большую историю применения этого метода и существование большого количества расчетных программ, предназначенных для дизайна ГРП, нефтедобывающие и нефтесервисные компании зачастую сталкиваются с проблемами при проведении гидроразрыва, ряд из которых связан с недостаточной проработанностью физических моделей, заложенных в программные пакеты. В Институте динамики геосфер имени академика М.А. Садовского Российской академии наук создана уникальная установка, позволяющая проводить эксперименты по гидроразрыву пласта на образцах искусственного пористого материала, подобранного в соответствии с критериями подобия. Образцы имеют форму дисков диаметром 430 мм и высотой 72 мм, установка позволяет нагружать образцы по трем независимым осям, создавать градиенты порового давления, измерять поровое давление жидкости на сетке точек, регистрировать акустическую эмиссию, зондировать образец акустическими импульсами. В статье рассматриваются результаты экспериментов, проводимых на этой установке, показана необходимость усложнения моделей, применяемых для описания процесса образования и распространения трещин ГРП в проницаемом пласте в условиях сложного напряженного состояния. Представлены также результаты экспериментов по исследованию взаимодействия трещины гидроразрыва с созданными в модельном образце нарушениями сплошности.

Ключевые слова: гидроразрыв пласта; лабораторное моделирование; пористые среды; напряженно-деформированное состояние; разрушение