Laboratory stands for hydraulic fracturing simulation in a nonuniform stress field

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Abstract. The paper considers the capabilities of well-known laboratory facilities for hydraulic fracturing modeling under the true triaxial loading conditions. Of greatest interest are the stands that allow you to create a crack in large cubic samples with an edge length of 200 mm or more. In this case, it is possible to reduce the influence of edge effects from the boundaries of the sample on the propagation path of the discontinuity. The review includes research results obtained using 10 different facilities located in major scientific centers.

1. Introduction
An important element in the development of a successful hydraulic fracturing (HF) technology is laboratory studies of the formation and propagation of cracks in rock samples under compression. In most cases, tests are carried out on a cylindrical specimen, which is subjected to axial loading and uniform compression along the lateral surface of the core. Therefore, stresses act only in two independent directions during the experiment, which does not fully correspond to the reservoir conditions. The orientation of a hydraulic fracture is strongly dependent on the stress field; that is why it is necessary to use triaxial independent loading and large samples to neglect the influence of boundaries edge effects on the fracture trajectory for reliable physical modeling of hydraulic fracturing.

This paper discusses the capabilities of laboratory facilities for HF modeling, which allow to carry out research on cubic specimens with an edge length over 200 mm in a nonuniform stress field. The list of installations and their main characteristics are shown in the Table 1.

2. Types of laboratory facilities for the study of the HF process
The experiments performed on large-sized samples are varied. The influence of the design of sealing elements on the formation and propagation of a crack was established in laboratory tests carried out at the Chinakal Institute of Mining SB RAS (Russia, Novosibirsk) [1]. Models of downhole tools were made with different packer systems, including the use of several sealing elements in the form of polyurethane cylinders of different lengths with separating metal inserts between them. On the basis of experimental data, a comparative analysis of the methods for determining the shut-in pressure \( P_s \) used for stress measurement was carried out [2]. It was shown that the fracture pressure and the direction of fracture propagation depend on the shape of the bottom of the model borehole, the presence and direction of initiating slots on its wall, and the value of compressive stresses [3].
Table 1. Laboratory facilities for the study of hydraulic fracturing in an inhomogeneous stress field

| Institution (Country) | Sample size, mm | Loading, kN |
|----------------------|----------------|-------------|
| Chinakal Institute of Mining SB RAS (Russia) [1, 3] | 200 | 100 |
| Colorado School of Mines (USA) [4–6] | 200 | 1400 |
| Chongqing University (China) [7] | 200 | 6000 |
| Tohoku University (Japan) [8] | 200 | 400 |
| Central South University (China) [9] | 300 | 1000 |
| China University of Mining and Technology (China) [10–12] | 300-500 | 4000 |
| China University of Petroleum (China) [13–16] | 300 | 2300 |
| Jilin University (China) [17] | 300 | 5400 |
| Wuhan University of Technology (China) [18] | 300 | 3000 |
| Research Institute of Petroleum Exploration and Development (China) [19] | 762 | 40000 |

At the Colorado School of Mines (USA) a series of experiments on fracturing rocks with liquid nitrogen was carried out (Figure 1a) [4, 5]. This technology is used to prevent a rapid decline in the production of oil and gas reservoirs after HF, as well as to reduce the risks of contamination of groundwater. The tests were carried out on samples of shale, sandstone and concrete in a non-uniform stress field; the trajectory of crack propagation was recorded using acoustic methods, visual inspection and X-ray computed tomography. It was found that when creating cracks with liquid nitrogen, the breakdown pressure decrease was about 40% compared to the fracture with gaseous nitrogen. It is noted that during the experiments, extensive fracturing was not observed in the samples due to the phase transition of nitrogen. Therefore, if it is necessary to form more extended fractures, the injection pressure should be higher. In shale samples after hydraulic fracturing, an increase in permeability up to 300% was observed, while each repeated injection cycle led to an ever greater growth, associated not only with the formation of new fractures, but also with an increase in the opening of old ones.

The laboratory setup developed at Chongqing University (China) makes it possible to study the deformation of the sample, determine its permeability and simulate HF at loads up to 6000 kN (Figure 1b) [7].

Figure 1. Laboratory facilities for the study of the process of hydraulic fracturing at the Colorado School of Mines (a) and Chongqing University (b).

The maximum pumping pressure of the working fluid is 60 MPa. The results of studies of the permeability of shale samples showed its significant drop (up to 91%) with an increase in compressive pressures from 10 to 60 MPa. When performing hydraulic fracturing of samples, the predominant
direction of crack development and its dependence on the magnitude of the acting stresses were established.

Research at the Tohoku University (Japan) was carried out on artificial samples with specified properties (Figure 2a) [8]. To create the matrix of the samples, a mixture of quartz sand and kaolinite was used in a ratio of 10:1, while the interlayers were created from pure kaolinite. After hydraulic fracturing, the propagation of the crack and the distribution of the working fluid in the sample were investigated by visual methods. It was found that the crack tends to grow in the horizontal plane along the boundary of two layers, which may be associated with a low compressive vertical load during the experiment.

An increase in the sample size up to 300 mm and more imposes additional design requirements on the stands being developed. A laboratory setup created at Central South University (China) allows to perform hydraulic fracturing by supplying a variable flow of a working fluid with specified parameters [9]. The experiment was carried out on natural and artificial coal samples. As a result of the research, the authors proposed a pulsating HF technology (two-stage injection) with a variable frequency of the working fluid supply. Prior to the creation of the main fracture, injection occurs in a pulsed mode with pressure control, which allows reducing the fracturing pressure, and also contributes to the large-scale development of microcracks near the wellbore. After the fracture formation, injection is carried out at a controlled rate to monitor the volume of the created fracture, while the pulsation frequency can be changed to achieve the maximum effect.

An extensive research program is being carried out at the China University of Mining and Technology. A photograph of the laboratory setup is shown in Figure 2b. The features of the development of a hydraulic fracture in samples with preliminary destruction were studied. To do this, a microexplosion was performed in the borehole filled with water before carrying out HF [10]. When comparing the results of HF of previously fractured samples and those samples that were not subject to such impact, significant differences were observed. Thus, an extensive system of additional cracks is formed during microexplosion in the vicinity of the well, and further fracturing creates up to 8 fracture planes in the sample, in contrast to one crack in the samples without preliminary destruction.

A laboratory experiment on simultaneous hydraulic fracturing in several wells located on the same line showed the following results [11]. Large cubic specimens with a rib length of 500 mm made of concrete were used. During the research, the main features of the formation and propagation of cracks were established. The following variants were observed: the formation of a single main crack connecting all boreholes; mutual formation of the main crack and cracks in the direction perpendicular

Figure 2. Laboratory facilities for HF experiments at Tohoku University (a) and China University of Mining and Technology (b).
to the direction of the minimum compressive stress $\sigma_3$; fracturing only in the direction perpendicular to the direction of $\sigma_3$.

Another series of experiments was devoted to the fracturing of artificial samples with high pressure air [12]. The results obtained were compared with the results of standard water fracturing. The injection rates were 25 l/min for air and 400 ml/min for water. It has been found that the pressure-time diagrams, the energy of acoustic emission and the nature of crack propagation for two different media are significantly different. During air fracturing increased values of the acoustic emission energy were observed and the length of the cracks formed was shorter than when the sample was fractured with water.

The results of testing samples obtained using a laboratory setup of the China University of Petroleum are more applicable to solving urgent problems of the oil and gas industry. During experiments the influence of the stress state, the ratio of horizontal stresses, the rate of injection and the viscosity of the working fluid on the direction and nature of the propagation of cracks in shale was studied [13]. X-ray computed tomography was used to study the complex structure of the formed microcracks and control the final trajectory of the main crack. The influence of artificial and natural fracturing on the development of hydraulic fractures was studied in [14], and the system of artificial fractures was created by heating and cooling the samples.

In another experiment, shale samples with clearly defined layering were subjected to HF with fracturing fluids with different viscosities and carbon dioxide in a supercritical state [15]. It was found that at high vertical stresses, the crack crosses the horizontal layering, and its deviations towards bedding are observed with a decrease in the vertical compression of the sample. This is consistent with theoretical data. The use of more viscous working fluids and high injection rates is preferable to create one main fracture, otherwise additional fractures and branches may appear. When fracturing with carbon dioxide, its use leads to the formation of a wide network of cracks in the sample, which is a favorable factor for solving some problems.

The results of some studies can be used to develop effective technologies for the extraction of coal bed methane [16]. When conducting laboratory experiments on six samples made of natural anthracite and artificial rocks representing the roof and floor, it was found that the presence of natural fracturing and the magnitude of the stresses are the determining factors for the direction of fracture development. Based on the results, it is planned to adjust the rate of injection of the working fluid at the coal methane field in the Changzhi province in order to prevent excessive fracturing outside the coal seam.

A series of experiments on the destruction of granite blocks with their heating up to 150°C was carried out on a laboratory setup developed at Jilin University (China) [17]. The main objective of the research was to determine the features of fracture propagation with an increase of the injection rate of the working fluid. According to the results, the injection rate affects the geometry and direction of fracture development, as well as the number of micro-fractures created close to the model borehole.

A laboratory facility at the Wuhan University of Technology (China) was used to conduct experiments on large blocks of coal (Figure 3a) [18]. It was noted that the fracture trajectory was significantly influenced by the values of the maximum and minimum horizontal stresses. In the case when these stresses were close, the geometry of the crack was complex and the crack did not have a clear direction. The influence of the injection rate on the direction of propagation of the main fracture and the development of an additional network of fractures was established.

A setup for HF modeling on extra-large samples was developed at the Research Institute of Petroleum Exploration and Development, China (Figure 3b) [19]. The sample size is 762x762x914 mm, the working fluid pressure is up to 69 MPa, and the injection rate is up to 10 l/min. When simulating reservoir conditions, the pressure on the sample wall can reach 69 MPa. Such parameters help to obtain unique data that can be used to improve the technology of hydraulic fracturing. For example, the results of studies of the perforation process allowed the development of a new method of crack initiation, in which the recorded breakdown pressure was significantly lower than with standard perforation technique.
Figure 3. HF laboratory stands at facilities for HF experiments at Wuhan University of Technology (a) and Research Institute of Petroleum Exploration and Development (b).

3. Conclusions
Analysis of the known laboratory studies of HF showed that there are not many facilities that have a possibility to perform experiments in large cubic samples under the true triaxial loading conditions. Most of them are designed for testing in samples with a rib length of up to 300 mm, and hydraulic fracturing is almost always carried out in a single borehole. This does not allow studying the issues of interaction of cracks during synchronous or staged fracturing of several wells. Installations with the ability to test specimens larger than 300 mm are isolated and are used to solve specific issues, for example, to establish the features of the initiation and growth of cracks in the presence of perforations of various directions and depths which is of great practical interest.

Obviously, an increase in the size of the sample allows us to designate a number of new areas of research. In a large sample, it is possible to create artificial heterogeneities with specified properties, proppant-propped fractures, isolated cavities filled with liquid or gas and other inclusions which will help studying the effect of such structures on the fracture trajectory. The results can be used to solve urgent mining problems associated with increasing the efficiency of mine hydraulic fracturing to intensify the degassing of the coal-rock mass [20], creating fractures near existing heterogeneities in the seam, protecting mine workings from the emergence of natural and artificial cracks in them [21].

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