Experimental study on physical simulation of shale gas hydraulic fracturing

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Abstract. Physical simulation of hydraulic fracturing based on the feature of shale gas reservoir is an effective means to comprehend fracture geometry and extension mechanism, which is also one of the most effective methods for shale gas reservoir reconstruction. Take hydraulic fracturing construction as reference and select critical factor for object, shale gas hydraulic fracturing experimental system was designed. The system consists of true triaxial module, hydraulic servo pump module and acoustic emission module. By setting up different parameters of fracturing in simulation experiment, the influence of parameter factors on hydraulic fracturing effect is studied. The results show that type and quantity of perforation, size and direction of in-situ stress, fracturing fluid displacement and other parameters have different influence on the fracturing effect. This experiment provides a certain theoretical basis for shale gas hydraulic fracturing technology in construction site.

1. Introduction

Hydraulic fracturing technology is one of the core technologies for shale gas development. Different from conventional methods of oil and gas development, development of unconventional oil and gas reservoirs such as shale gas often requires the use of large-scale hydraulic fracturing to transform reservoirs, pursue complex structures and form cracks that intersect with natural fractures and artificial fractures. The network will break effective reservoir, increase its seepage area and diversion capacity to increase initial production and ultimate recovery.

Hydraulic fracturing technology uses advanced fracturing equipment to inject various fracturing fluids containing additives into shale formation to expand fractures in reservoirs under specific high-pressure conditions, thereby fully connecting natural fractures and new hydraulic fracturing fractures. Depending on the characteristic proppant supporting fractures, the reservoir fracture network system is improved, so as to achieve the purpose of increasing volume of transformation as much as possible to increase production. After hydraulic fracturing, cracks show various complex forms, usually longitudinal cracks, transverse cracks, turning cracks and twisted cracks. They are not only closely related to state of in-situ stress, wellbore orientation and fracturing technology, but also effects of perforation phase, density and natural fractures. The cracks are determinants of yield.

However, horizontal well fracturing technology for shale gas reservoirs with self-generating, self-reserving, deep burial depth and saturated adsorption-accumulation geology characteristics has just started. Hydraulic fracturing technology is not yet mature, especially for hydraulic fracturing cracks.
The shape and expansion laws are still unclear. It is necessary to carry out physical simulation experiments on shale gas hydraulic fracturing. The physical hydraulic fracturing simulation test of shale reservoir characteristics can determine shale fracture ability, fracture pressure and fracturing effects, which is a reliable way to understand the geometric shape and extension rule of shale fractures. Effective measures can also provide experimental basis for field fracturing construction. In this paper, different perforation patterns, confining pressure and displacement are set to study the effects of different fracturing parameters on fracturing effect and provide experimental evidence for development of continental shale gas in Ordos Basin, the target block.

2. Hydraulic fracturing physical simulation test system

2.1. The main experimental equipment

Using hydraulic fracturing physics simulation test system jointly developed by China University of Geosciences (Wuhan) and Nantong Huaxing Petroleum Instrument Co., Ltd., the physical simulation of hydraulic fracturing process can be realized under laboratory conditions, as shown in Figure 1. The system includes a large-size true three-axis module, a hydraulic servo pump pressure module, an AE acoustic emission module and a control device. The large-size true three-axis module includes a sample chamber, a square block for pressurizing sample and a hydraulic piston pump connected to square block to drive the sample to pressurize. Three square blocks press the specimen in three directions to simulate three directions of ground stress ($\sigma_{Hmax}$, $\sigma_{hmax}$, $\sigma_h$), each square block corresponds to a hydraulic pump. Oil paths in three directions are independent of each other and can not affect each other. In this way, three-dimensional confining pressure is applied to specimen to simulate ground stress. The acoustic emission module includes an acoustic emission probe installed in a large-size true triaxial test specimen placement room, a full information acoustic emission analyzer host and control computer which are electrically connected to the probe. During hydraulic fracturing process, the acoustic emission probe receives acoustic signal from cracks and transmit to the host of acoustic emission analyzer. The signal is transmitted to the computer after analysis. Then location map of hydraulic fracturing crack can be displayed to realize the monitoring of the hydraulic fracturing process. The hydraulic servo pump pressure module includes a tank and a high-pressure injection pump for injecting fresh water fracturing fluid into a simulated wellbore in the sample. The modules cooperate with each other to jointly complete physical simulation test of shale hydraulic fracturing.

![Figure 1. Hydraulic fracturing physics simulation test system](image)

2.2. Simulation sample making

In order to make physical and mechanical parameters and in-situ stress conditions of shale reservoirs have same properties as those of indoor fracturing rock samples, such as density, elastic modulus and Poisson's ratio, typical outcrop shales are used as experimental simulations. By adjusting ratio of water, ash and sand, strength of cement sample is similar to the original rock and the size of the artificial cement sample is 300mm * 300mm * 300mm. Cement samples require high strength, small deformation, low porosity and low permeability. Main materials are fine quartz sand, quick-hard 42.5
Portland cement, barite powder and water. First, initially select a group of mix ratios, conduct the first set of simulated sample production, stir evenly with a blender and pour into 150*150*150mm steel molds with mechanically and manually refilling at the same time. After cooling, the mold is removed and cured for 28 days at room temperature of 20°C and humidity of 99%. The degree of agreement between two physical properties is compared and analyzed. Based on error results, the mixing ratio of the sample is continuously adjusted. Secondly, on basis of the previous set of samples, physical properties of two sets of simulated rock samples are re-circulated and physical properties of three samples are quantitatively analyzed. Finally, a set of cement sample with physical properties most similar to those of shale is determined and the mix ratio parameters are used as standard parameters to simulate the mix ratio of the rock samples.

2.3. Simulation of rock sample design

In this simulation experiment, different perforation parameters, simulated ground stresses of different sizes and directions, displacements are designed to study hydraulic fracturing mechanism of shale under the condition that lithology characteristics are not changed. The acoustic emission location map and crack propagation patterns of the fractured specimens are used to investigate the process of extension cracking and basic laws of the simulation of shale hydraulic fracturing. The detailed parameters of the samples are shown in Table 1.

Table 1. Sample parameter table

| specimen number | length of wellbore (mm) | perforation type | phase angle | number of perforations |
|-----------------|-------------------------|------------------|-------------|-----------------------|
| A1              | 250                     | Single Wing      | 0°          | 8                     |
| A2              | (mm)                    | Double wings     | 180°        | 16                    |
| A3              | 185                     | Single Wing      | 0°          | 4                     |
| A4              | (mm)                    | Double wings     | 180°        | 8                     |
| A5              | 250                     | Single Wing      | 0°          | 8                     |
| A6              | (mm)                    | Double wings     | 180°        | 16                    |
| A7              | 185                     | Single Wing      | 0°          | 4                     |
| A8              | (mm)                    | Double wings     | 180°        | 8                     |
| B1              |                         |                  | 30°         | 4                     |
| B2              | 185                     | Spiral           | 45°         | 4                     |
| B3              | (mm)                    |                  | 60°         |                       |
| B4              |                         |                  | 90°         |                       |

The hydraulic fracturing test needs to make simulated wellbore with different parameters. The parameters specifically include wellbore length and perforation phase angle, as shown in Figure 2. During preparation of the cement samples, simulated wellbores with different parameters are preset therein. After all the samples are prepared and solidified, they are demoulded and put into a thermostatic chamber. The temperature is controlled at about 20°C and the humidity is maintained at 99%. In 28 days, hydraulic fracturing physics simulation tests are conducted after design strength is reached.

(a) Single-wing wellbore (b) Double-wings borehole (c) 45° phase angle wellbore

Figure 2. Simulation wellbore physical map
2.4. Test methods
First, a small amount of red tracer dye is injected into the simulated wellbore. Then connect the wellbore out of the sample and the high-pressure injection pump joint with steel pipes using threads. The sample is loaded into a large-size true three-axis physical simulation test system. Secondly, set the parameters which includes the specimen number, the confining pressure of three directions and pump injection displacement. Pre-press the sample so that fracturing fluid fills the injection line. Set each direction of the sample according to the experimental design. Turn on the acoustic emission analyser host and enter the acquisition mode on the pressure, then ready for testing. Make the high-pressure injection pump into fracturing mode again, the high-pressure fluid enters the sample for fracturing when the pump pressure curve suddenly drops and basically stays at a constant pressure value, then depressurize the pump and stop collecting. The test is completed. Finally, the sample is taken out and cut open. An accurate and intuitive test is obtained based on the position of the red tracer and the acoustic emission location point. After taking out the specimen, the fracture morphology of the specimen is obtained accurately and intuitively according to the position of the red tracer and the positioning point of acoustic emission. Then the fracture mechanism and the influence factors of the crack formation are analyzed.

| specimen number | $\sigma_{f_{\text{max}}}$ (Mpa) | $\sigma_{f_{\text{max}}}$ (Mpa) | $\sigma_h$ (Mpa) | displacement (ml/s) |
|-----------------|-------------------------------|-------------------------------|-----------------|-------------------|
| A1              | 8                             | 4                             | 6               | 2                 |
| A2              | 8                             | 4                             | 6               | 4                 |
| A3              | 8                             | 4                             | 6               | 5                 |
| A4              | 10                            | 4                             | 6               | 4                 |
| A5              | 12                            | 8                             | 10              | 2                 |
| A6              | 12                            | 8                             | 10              | 4                 |
| A7              | 12                            | 8                             | 10              | 5                 |
| A8              | 15                            | 8                             | 10              | 4                 |
| B1              | 8                             | 4                             | 6               | 2                 |
| B2              | 8                             | 4                             | 6               | 2                 |
| B3              | 12                            | 8                             | 10              | 4                 |
| B4              | 15                            | 8                             | 10              | 5                 |

3. Test results analysis
3.1. Summary of main test results

(a) A2  (b) A5  (c) A7
After hydraulic fracturing is completed, record the hydraulic fracturing process of the sample. Because of damage of the samples and leakage of the fracturing fluid, six representative specimens are chosen to show in Table 3 and Figure 3. The most representative specimen B1 is selected for analysis. The specimen B1 represents perforations distributed within the space. The sample is cut along the surface cracks and then the fracture patterns of the type of perforation is studied based on the position of the red tracer.

Table 3. Results of hydraulic fracturing simulation

| specimen number | fracturing pressure (Mpa) | number of side cracks | extravasation of fracturing fluid | situation description                                                                 |
|-----------------|--------------------------|-----------------------|-----------------------------------|--------------------------------------------------------------------------------------|
| A2              | 8.80                     | 2                     | Mass                              | Fracturing fluid ejects during fracturing, two small and straight cracks open on both sides of wellbore |
| A5              | 16.40                    | 3                     | Mass                              | The fracturing fluid overflows from the middle of the side during fracturing and there is a small crack |
| A7              | 36.60                    | 3                     | Mass                              | There are obvious cracking sounds during fracturing, crack pressure is large, apparent cracks appear on the surface of the sample |
| B1              | 32.70                    | 1                     | Small                             | There are weak cracking sounds during fracturing, the surface crack is extremely small, and it is distributed on the surface of the wellbore upper mouth |
| B3              | 30.50                    | 3                     | Mass                              | There are noticeable cracking sounds in the fracturing process, in which one crack penetrates and the other two are distributed on two adjacent sides. |
| B4              | 22.50                    | 1                     | Mass                              | There are two cracking sounds in the fracturing process and there is a tiny crack on the surface of the upper hole of the wellbore |
3.2. Analysis of typical sample results

In the sample B1, the angle between the perforations on simulated wellbore is 30° and it is arranged spirally. The initial perforation intersects with the positive direction of the X-axis at 30° and is perpendicular to the Z-axis. The simulation results of hydraulic fracturing in the rock sample B1 are shown in Figure 4.

| Sample number | Wellbore type | Well length | σHmax / σhmax / σh | Displacement |
|---------------|---------------|-------------|---------------------|--------------|
| B1            | Space spiral  | 185mm       | 8/4/6(Mpa)          | 2 (ml/s)     |

From the test results, it can be seen that the two perforations close to the wellhead form a seepage channel 1 after hydraulic fracturing, and the other two perforations form a seepage channel 2. Since the pump injection force is greater than the uniaxial compressive strength of the specimen, shear damage occurs near the perforation and initial cracks are formed along the perforation direction. The fracturing fluid must infiltrate into the initial crack. When penetrating water pressure at the tip is greater than the fracture toughness value of the simulated rock sample, the fracture will expand a certain distance forward and randomly form new fractures. Then the fracture gradually evolves into curved seepage channel 1 and channel 2. At the same time, in the direction of the combined force of the two seepage channels, an equilibrium force F3 equal to F is expected. When F3 is greater than the uniaxial tensile strength of the sample, the combined pressure of seepage water tensile failure occurs in the direction, resulting in a tear-type hydraulic fracture, which gradually expands and eventually evolves into a percolation channel 3, but forms in a flat plane. This is very different from the extension of the main crack. The internal force balance diagram of the sample during fracturing is shown in the figure 4.

Figure 4. B1 Simulation test results of hydraulic fracturing in rock samples
From the curve of pump pressure vs. time, Figure 5, we can see that after the start of the test, the initial pressure is about 0.44MPa. With the increasing of fracturing fluid, the injected liquid is greater than the loss of liquid and the pump pressure gradually increases linearly. After reaching a peak value of 32.7MPa, the initial cracks begin to form and the pressure falls back to 23.90MPa. With the increasing of the fracturing fluid, the cracks extend forward. The pump pressure rises linearly to 24.9MPa at 15 seconds and the pressure begins to slowly decline again at 20 seconds. At this stage, the fracturing fluid continues to pump in, the cracks continue to extend forward and the new cracks come into being. This is due to the rupture in the opposite direction of the resultant force in the process of increasing water pressure, which results in new cracks. After 23 seconds, the pressure remains at 25.0MPa. After the cracks form, they evolve into osmosis channels of fracturing fluid. The fracturing fluid penetrate into the exterior of rock sample along this passage, resulting in large spills, then the pump is stopped.

![Figure 5. Curve of pump pressure vs. time and accumulated water injection](image)

4. Main conclusions and prospects
Based on mechanical properties of original rock at the site of target block, physical simulation experiment of large-scale true triaxial shale hydraulic fracturing is carried out. Effects of perforation, confining pressure and displacement on the hydraulic fracturing are compared and summarized. After research, draw the following conclusions.

(1) General law of hydraulic fracture formation is that under an action of pump pressure, specimen starts to crack after tensile failure in the direction of perforation. After an initial crack is formed, the fracturing fluid seeps into the initial crack. When the seepage water pressure strength at the crack tip is larger than fracture toughness value of the simulated rock sample, the crack will extend and gradually shift to the direction of maximum principal stress during the course of extension and gradually evolve into a percolation channel.

(2) The curve of pump pressure vs. time shows a significant difference due to the type of perforation. The degree of fluctuation is positively related to complexity of the hydraulic fracture. The shear fracture of hydraulic cracks during the extension process, or the connection of natural cracks and layered weak surfaces will make the curves show different forms. Shape of hydraulic fracture can be preliminarily predicted by curve of pump pressure vs. time.

(3) Perforating parameters, stress differences and displacement can have different effects on hydraulic fracturing tests. Among them, the perforation parameter is a decisive factor influencing fracture morphology. The cracks formed by plane perforation are regular in shape and approximate straight line. Cracks formed by spiral perforations are massive and irregular. Therefore, spatial pattern perforation is more likely to produce complex crack patterns than planar perforation pattern. In the spatial pattern perforation, when phase angle \( \theta < 45^\circ \), inter-slit interference between adjacent perforations is easy to occur and the cracks also easily connect with each other near the wellbore.
When $\theta \geq 45^\circ$, the inter-slit interference is weakened, the number and scale of cracks increased. Maximum stress difference can change the direction of extension of hydraulic fracture so that the hydraulic fracture eventually deflects toward the direction of maximum principal stress. Size of pump injection flow rate determines crack size. Low-displacement volume facilitates seepage of the fracturing fluid in the simulated sample. Compared with large displacement, it is easier to form complex cracks.

Acknowledgements
This research was supported by China National High Technology Research and Development Program 863(No.2013AA064503). And thanks to the platform provided by National College Students' Innovation and Entrepreneurship Program.

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