Hydraulic fracturing fracture propagation in tight sandstone reservoir

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Abstract. The tight sandstone reservoir of Shaximiao Formation of Middle Jurassic in Qiulin block of central Sichuan Basin, with a burial depth about 2200 to 2300 m, is characterized by undeveloped natural fractures. It is difficult to form complex fracture network during the implementation of traditional volume fracturing technology, affecting the benefit of tight sandstone gas development. A series of true triaxial hydraulic fracturing tests were conducted on the sandstone outcrop (dimensions: 300 mm × 300 mm × 300 mm), collected from this block, to investigate the initiation and propagation law of hydraulic fracture in tight sandstone reservoir under different conditions. Experimental results indicate that the peak value disturbance and increasing stress shadow in the back section of the pump pressure curve of staged multi-cluster fracturing in horizontal wells of sandstone reservoir will dominate the fracture morphology. The small interval leads to the increase in dynamic hydrostatic pressure on the fracture wall and increase in the deflection angle and degree of multi-cluster fractures, and it is easy to form crosscut fractures. The symmetrical middle segment perforation cluster inhibits the initiation and expansion of fractures, and the fractures will extend perpendicular to the maximum horizontal in situ stress direction and gradually approach the fractures on both sides and finally stop expanding. High-viscosity fracturing fluid is easy to form high hydrostatic pressure in the perforated section, reducing the difficulty of fracture initiation. The angle between the borehole and the minimum horizontal in situ stress (σh) will affect the propagation direction of hydraulic fractures. When the angle is large, the propagation direction of fractures is easily affected by the natural weak surface and induced stress field, resulting in fracture diversion. This study has mastered the initiation and propagation mechanism of artificial hydraulic fractures in tight sandstone reservoir, established the optimization chart of fracturing parameters in sandstone reservoir, and has certain guiding significance for the establishment of on-site fine optimization fracturing scheme design.

Key words: Tight sandstone gas; Triaxial hydraulic fracturing experiment; Construction parameters; Fracture morphology; Pump pressure curve

1. Introduction
As an important substitute for conventional oil and gas resources, tight oil and gas can be developed efficiently only by using reservoir modification technologies such as hydraulic fracturing. However, the conventional fracturing technology based on linear elastic fracture mechanics assumes that the artificial fracture is open, and the double wing symmetric fracture is formed along the perforated interval of wellbore, making the conventional fracturing technology appear obviously inadaptable in tight sandstone reservoir with undeveloped natural fracture. Oilfield exploration and development practice shows that horizontal well and staged volume fracturing technology are the key technologies to improve the development efficiency of this kind of reservoir [1-7]. The natural factors influencing fracture network morphology after fracturing include horizontal in situ stress difference, brittle
mineral content in rock, bedding in reservoir, natural fractures, and other discontinuous structural planes [8-12]. In addition, the fracture network shape is also affected by construction parameters and technology [13-15]. Laboratory hydraulic fracturing physical simulation test is the most important and effective means to study fracture propagation mechanism. At present, scholars at home and abroad have conducted a large number of fracturing simulation tests on shale [9,16-18], coal [19-21], and concrete [22-23]. They also carried out some research work on the initiation and propagation law of hydraulic fractures under relevant lithological conditions. Therefore, in order to solve the problem of volume fracturing in Shaximiao formation tight sandstone reservoir in the middle of Sichuan Basin, the outcrop samples of Shaximiao formation tight sandstone were selected to carry out the physical simulation experiment of true triaxial hydraulic fracturing and to explore the initiation law of hydraulic fractures under the action of fracturing fluid viscosity, horizontal well trajectory, interval between staged fracturing sections, and other construction parameters. Mastering the geometry of hydraulic fracture propagation under indoor conditions can provide some guidance for fracturing site construction.

2. Rock sample preparation and experimental scheme design

The true triaxial fracturing simulation system is used to simulate the hydraulic fracturing of tight sandstone outcrop. The experimental core is extracted from Sichuan Basin, with a size of 300 mm × 300 mm. The diameter of 14-mm well is drilled in the middle of a natural core with a depth of 170 mm. The simulated well is made of self-developed integrated stainless steel high-pressure resistant well. The simulated well is inserted into the prefabricated well, cemented, and sealed with plants. At the same time, 50-mm open hole is reserved with water-soluble NaCl (Fig. 1).

Fig. 1 Schematic diagram of sample processing

There are four sandstone outcrop samples in the experiment. Figure 2 shows the direction of borehole trajectory and angle. The relevant data of tight sandstone reservoir in Shaximiao formation are as follows: the reservoir rock type is mainly medium- to fine-grained arkose, followed by lithic arkose. Quartz, feldspar, and cuttings account for 45.0%, 33.3%, and 21.3% of the mineral components, respectively. The content of brittle minerals is relatively high. Reservoir porosity is mainly between 8% and 15%, with an average of 11.3% [5]. According to the actual parameters of the above strata, the laboratory experimental parameters are calculated using similarity criterion [24]. Through the physical simulation experiment of hydraulic fracturing of tight sandstone, the influence of different fracturing fluid viscosity, different borehole angle, different density cutting, and other parameters on the fracture propagation law of hydraulic fracturing is evaluated. Table 1 summarizes the specific experimental parameters. Figure 2 shows the angle between wellbore trajectory and minimum horizontal geostress. The experimental fracturing fluid medium is a slippery hydraulic fracturing fluid system, and its formula is 0.06% guar gum mixed with distilled water. In order to better track the hydraulic fractures, green tracer is added into the fracturing fluid, and the displacement remains unchanged during the fracturing process. The main influencing factors of fracture growth
morphology are evaluated by the fracture morphology expansion law and pump pressure curve characteristics of the sample after fracturing.

Fig. 2 Angle between wellbore trajectory and minimum horizontal geostress

| Sample number | Well type | Fracturing fluid viscosity (MPa.s) | In situ stress (MPa) | In situ stress difference (MPa) | Pump rate (ml/min) | Angle (Deg) | Close-cut number |
|---------------|-----------|-----------------------------------|---------------------|-------------------------------|-------------------|-------------|-----------------|
| (1#)          | Horizontal | 10.5                              | 20/25/17            | 8                             | 35                | 30          | 3               |
| (2#)          | Horizontal | 10.5                              | 20/25/17            | 8                             | 35                | 45          | 3               |
| (3#)          | well      | 10.5                              | 20/25/17            | 8                             | 35                | 0           | 3               |
| (4#)          |           | 35                                | 20/25/17            | 8                             | 35                | 0           | 6               |

3. Experimental results and analysis

3.1. The experimental result

During the experiment, the fracturing fluid was injected into the well with the displacement of 35 ml/min. With the injection of fracturing fluid, the injection pressure increased continuously. When the peak value of pressure curve dropped sharply and did not rise, the whole fracturing simulation was completed. After the experiment, the tool was used to open the fracture sample along the fracture surface and the fracture morphology, that is, the trace of tracer on the fracture surface was observed. It was found that the fracture morphology could be divided into four types, namely, transverse fracture, vertical fracture, \( \parallel \) fracture, T fracture. Table 2 presents the typical fracture morphology after fracturing.
Table 2 Statistical table of hydraulic fracturing physical simulation experiment results

| Sample number | Pump pressure curve | Photos of fractured samples |
|---------------|---------------------|----------------------------|
| (1#)          |                     |                             |
| (2#)          |                     |                             |
| (3#)          |                     |                             |
| (4#)          |                     |                             |

When the viscosity of fracturing fluid is 10.5 MPa.s, and the angle between wellbore and well is 30. Under the condition that the number of dense cuts is 3, a crosscut fracture is initiated at the second perforation, and the fracture extends to the boundary of the 1# sample. There are many groups of small-scale fractures along the bedding plane on the fracture surface around the wellbore and finally converge with the main fracture surface. According to the pump pressure curve, when the injection time is 3.75 min, fracture appears on the rock sample, the fracture pressure is 18.89 MPa, and then the injection pressure drops sharply to about 12 MPa. The fracture then extends to the boundary of the rock sample with this pressure.
When the viscosity of fracturing fluid is 10.5 MPa.s, and the angle between wellbore and fracture is 45°. Under the condition that the number of close cuts is 3, the classical two-wing symmetrical seam is formed of sample 2#. Due to the seepage phenomenon in the slotted section, the hydraulic energy cannot be well condensed, and the crack does not start from the slotted section. According to the pump pressure curve, when the injection time is 10.35 min, the rock sample is fractured, the fracture pressure is 18.06 MPa, and then the injection pressure drops to about 15.5 MPa. The fracture then extends to the boundary of the rock sample with this pressure.

When the viscosity of fracturing fluid is 10.5 MPa.s, and the angle between wellbore and fracture is 0°. Under the condition that the number of dense cuts is 3, a crosscut fracture starts along the second perforation of sample 3#, and the fracture deflection occurs after the fracture front extends to the bedding plane and turn 90° on one side. It extends downward along the bedding plane and turns to 90° on the other side. It extends upward along the bedding weak plane. In addition, because the wellbore is parallel to the bedding, a symmetrical fracture with two wings is formed in the direction parallel to the weak plane of the bedding. Finally, the shape of the fracture is a "T" shape. From the pump pressure curve, the fracture pressure of the sample is 17.54 MPa. There are three pressure drops on the pump pressure curve, reflecting the crack propagation process inside the specimen.

When the viscosity of fracturing fluid is 35 MPa.s, and the angle between wellbore and fracture is 0°. Under the condition of dense cutting number of 6, a crosscut fracture of 4# sample cracks along the second perforation, and the fracture deflection occurs after the fracture front extends to the bedding plane, forming a two-wing symmetric fracture parallel to the weak plane of bedding. This makes the fracture shape of the sample almost T-shaped. From the pump pressure curve, the fracture pressure of the sample is 15 MPa. There are two pressure drops on the pump pressure curve, showing the formation and propagation process of cracks in the sample.

3.2 Influence of fracturing fluid viscosity

The expansion of hydraulic fractures follows the principle of minimum resistance. Compared with low permeability and ultralow permeability lithology, the permeability of tight sandstone reservoir in this block is relatively high, and high permeability channels are developed in some samples, as shown in Fig. 3. As a result, the filtration of fracturing fluid with low viscosity is serious, and the fracture initiation time of the sample is prolonged. The fracture morphology of 1# and 2# samples is single fracture after fracturing, while the high-viscosity fracturing fluid of 35 MPa.s is used for 4# samples, greatly reducing the filtration of fracturing fluid in the rock, forming a higher net pressure in the perforation section in a shorter time, and shortening the time to reach the fracture pressure of the sample. A complex crack network is formed in the sample.

![Fig. 3 Flow diagram of fracturing fluid](image)
3.3. Influence of borehole angle

The angle between the wellbore and the minimum horizontal geostress will affect the propagation direction of hydraulic fractures. Taking, for example, 1#, 2#, and 3# samples, when the angle between the wellbore trajectory and the minimum horizontal in stress is large, the propagation direction of fractures is more easily affected by the induced stress field. Under the condition of high horizontal stress difference, it is difficult for fractures to turn around the wellbore, so that the fracture shape is relatively single. Under the condition of high stress difference, the smaller the angle between borehole trajectory and minimum horizontal in situ stress, the greater the horizontal and vertical expansion distortion of fractures and the more the branch fractures. Fractures mainly expand in the initiation layer and are not easy to penetrate. Figure 4 shows the well trajectory-oriented fracturing operation chart.

![Fracture complexity](image)

Fig. 4 Influence of well trajectory on hydraulic fracture

3.4. The influence of fracture spacing

In the experiment, the larger the value of dense cutting, the smaller the spacing of fracture. By distributing more hydraulic fractures in a certain horizontal section, not only the contact area between hydraulic fractures and reservoir can be increased, but also the induced stress caused by the shortening of fracture spacing changes the in situ stress field. The stress shadow that is formed by induced stress can reduce the influence of horizontal stress difference in this area, which is more conducive to the formation of complex fractures. From the pump pressure curve, the typical peak value of pressure curve after multifracture initiation is an obvious feature of multifracture interference in tight sandstone. The small cluster spacing increases the adjacent cracks in the region of induced stress, which greatly increases the degree of stress interference and crack deflection, making it easier to form complex cracks.

3.5. The other influencing factors

Due to the low cementation strength of the bedding plane of tight sandstone, the tensile strength and fracture toughness of the bedding plane are far less than that of the matrix. Therefore, after the hydraulic fractures communicate with the bedding plane of tight sandstone, because the opening difficulty of the bedding plane is low and the ability to prevent the fracture expansion is weak, the hydraulic fractures make it easy to open the bedding plane, thus turning and bifurcating, forming a complex fracture network.
4. Conclusion

1. Compared with the low permeability reservoir, the tight sandstone reservoir in this block has good permeability, which easily leads to the filtration of fracturing fluid, prolongs the fracture initiation time of rock mass, dissipates hydraulic energy, and reduces the complexity of fractures. Nonetheless, the fracturing fluid system with high viscosity or low filtration should be given priority in the fracturing of such reservoirs.

2. The angle between the borehole and the minimum horizontal in stress will affect the propagation direction of hydraulic fractures. When the angle is small, the fracture propagation direction is more easily affected by the induced stress field and is less affected. Under the condition of high horizontal stress difference, the horizontal and vertical propagation of fractures is distorted, and there are many branch fractures. The fractures mainly expand in the initiation layer and are not easy to penetrate.

3. The fracture morphology of hydraulic fracture is mainly controlled by the difference of horizontal principal stress. When the difference of horizontal principal stress is 8 MPa, the fracture generally expands along the direction of vertical minimum principal stress, and the extension pressure fluctuation of the fracture is relatively stable. It is difficult for the induced stress to change the original principal stress, thus forming a single fracture. By shortening the cluster spacing, the adjacent cracks can be located in the induced stress increasing region, and the stress interference degree can be increased, so as to increase the deflection degree of cracks and to form a complex fracture network.

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