Study on non-plane propagation characteristics of fracturing fractures in tight sandstone of Qiulin block under high geo-stress

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**Abstract.** In order to study the propagation characteristics of hydraulic fracturing fractures in tight sandstone reservoirs in Qiulin block, Sichuan Basin, hydraulic fracturing of tight sandstone under high triaxial in-situ stress were carried out by using a large true triaxial fracturing physical experimental system. The fracture morphology and pump pressure curves under different in-situ stress, fracturing fluid types and displacement were obtained. The experimental results show that: (1) under high geo-stress conditions, the fracture morphology of tight sandstone after hydraulic fracturing is relatively simple, and complex fracture characteristics are less formed. The sedimentary characteristics and the development of internal natural fractures are the main control factors affecting the initiation and propagation of hydraulic fracturing fractures. (2) The characteristics of in-situ stress affect the fracture initiation and propagation direction. When the vertical in-situ stress is equal to the horizontal minimum principal stress, the horizontal fracturing fractures perpendicular to the vertical in-situ stress direction can be formed, and most of the fracturing fractures are non-plane propagation fractures. (3) When the low displacement slick water is used for fracturing, the fracturing fluid is easy to enter into the micro fractures inside the tight sandstone, which is helpful to open the original micro fractures, and the fracture morphology after fracturing is relatively complex; when the high displacement slick water or high viscosity linear gel is used for fracturing, the fractures with non-planar expansion are formed after fracturing. The research results can provide some technical support for the reservoir reconstruction of the second member of ES_2 formation in Qiulin block, Sichuan.

**Keywords.** Tight sandstone; High geo-stress; True triaxial; Hydraulic fracturing; Morphology scanning; Non planar fracture.
1. Introduction

Tight sandstone is an important unconventional oil and gas reservoir, which has been successfully developed in North America[1]. Tight sandstone gas reservoirs are widely distributed in China, especially in Ordos Basin and Sichuan Basin[2]. The porosity and permeability of tight sandstone reservoir are very low, and the matrix permeability is less than 0.1 mD. Generally, a single well has no natural productivity. Therefore, hydraulic fracturing technology should be used to transform the tight sandstone reservoir. By using large-scale fracturing equipment, fracturing fluid with certain characteristics is used to expand the fracturing fracture and natural fracture channel, increase the contact seepage area between wellbore and gas reservoir, so as to improve the gas production of reservoir and achieve the purpose of producing industrial gas flow[3]. The effect of fracturing operation directly affects whether the reservoir can be developed efficiently and economically. At present, there is no technical means to directly observe the hydraulic fracturing, which leads to the lack of understanding of the fracture initiation and propagation law. It is of great significance to study the fracture initiation and extension law to improve the effect of reservoir reconstruction.

In recent years, a large number of scholars have carried out effective research on the mechanism of hydraulic fracture initiation and propagation in tight reservoir. By using true triaxial hydraulic test, it is concluded that when the hydraulic main fracture extends vertically to the bedding plane, the weak bedding plane will bifurcate and turn, which communicates with the natural fracture and form a complex network fracture[3]. The physical simulation system of true triaxial hydraulic fracturing is constructed, and the technical methods of fracture characterization by acoustic emission location event and industrial CT scanning are proposed, which provides experimental basis for the study of fracture initiation and propagation in tight reservoir[4]. Y. L. Wei et al. carried out large-scale tight sandstone hydraulic fracturing experiment, the research shown that the fracture morphology of tight sandstone is single after fracturing, and there was less cross fracture[5]. H. Hazim and D. L. meadows studied the effect of directional perforating orientation on the initiation of hydraulic fractures. The results show that directional perforating can form main fracturing fractures in reservoirs, but not multiple parallel fractures and reorientation fractures[6]. Chitra M. used acoustic emission system to monitor the propagation of fracturing fractures in tight sandstone, and analyzed the surface morphology of fractured samples by SEM[7]. Li Zhi et al. studied the interaction mechanism between fracturing fractures and bedding plane, and determined the critical stress of tensile shear failure of bedding surface[8]. Through the experimental study of different phase CO2 fracturing in tight sandstone reservoir, the influence of horizontal geo-stress difference, fracturing fluid displacement and type on fracture propagation characteristics is discussed[9]. A three-dimensional discrete fracture network model (DFN) for hydraulic fracturing is established. It is considered that there is interaction between fracturing fracture and natural fracture[10-11]. Li et al. carried out hydraulic fracture propagation test of multi cluster fracturing in vertical wells, and the research shows that when the horizontal stress difference is greater than 6MPa, it is difficult to form a complex fracture system through multi cluster fracturing[12].

Through the summary and analysis of the existing research results, it is found that the loading stress of three-dimensional in-situ stress is generally low in hydraulic fracturing test, which cannot truly reflect the influence of absolute difference of in-situ stress on hydraulic fracture propagation. At present, the main field of gas exploration in the upper Triassic of Sichuan Basin is mainly concentrated in the central part of the basin. The buried depth of the reservoir is relatively deep, and the characteristics of in-situ stress are relatively complex, and there is a lack of accurate and effective on-site detection methods, so it is impossible to directly observe the hydraulic fracturing effect of tight sandstone reservoir. The true triaxial hydraulic fracturing system was used to carry out hydraulic fracturing experiments on tight sandstone and the characteristic parameters such as fracture morphology and pump pressure curve under different in-situ stress differences, fracturing fluid types and displacement were obtained, the main controlling factors affecting the propagation of fracturing fractures in tight sandstone are discussed. The research results can provide technical support for tight sandstone reservoir reconstruction in Qiulin area.
2. Sample preparation and test methods

2.1. Sample collection and preparation
The hydraulic fracturing samples are taken from outcrop of tight sandstone reservoir in Qiulin block. After hydraulic cutting, the tight sandstone obtained is processed into a 300 mm × 300 mm × 300 mm fracturing sample. The natural density is 2.403 g/cm³, the uniaxial compressive strength is 80.03 MPa, the elastic modulus is 13.78 GPa, and the tensile strength is 4.23 MPa.

The processed samples are shown in Figure 1, and a simulated horizontal wellbore with an outer diameter of 24 mm and a depth of 170 mm is drilled parallel to the sedimentary surface. The simulated casing is made of high strength steel pipe with an outer diameter of 20 mm and an inner diameter of 15 mm. The upper end is internally threaded for sealing connection with the pump pipeline of hydraulic fracturing pump pressure servo control system, and the casing is sealed with a high-strength adhesive to the prefabricated borehole. The sealing process and preparation of sample are shown in Figure 2.

2.2. Hydraulic fracturing experimental system
True triaxial fracturing test system is used to carry out hydraulic fracturing test of tight sandstone. The test system mainly includes true triaxial loading system and servo pump pumping system.

2.2.1. True triaxial in-situ stress loading system
The large geotechnical engineering model testing machine is a three-dimensional loading electro-hydraulic servo simulation testing machine, as shown in Figure 3. The main technical parameters are as follows:
(1) The three directions X (left and right), y (vertical) and Z (forward and backward) are independently pressurized by axial loading system, which can simulate the three-dimensional stress state of underground rock stratum.
(2) The maximum loading sample size can reach 500 mm × 500 mm × 500 mm, and the appropriate sample size can be selected according to the simulated situation. In this test, 300 mm × 300 mm × 300 mm cube specimens were used. The test is controlled and adjusted by computer automatically, and the data of stress and displacement are collected automatically.
(3) The maximum load of X, y and Z directions can reach 8000 kN, which can simulate the real high stress state of underground engineering.

(4) During the loading process, the axial loading force is uniformly transmitted to each surface of the sample through the connecting plate, force transfer plate and directional device in X, Y and Z directions.

![Figure 3. True triaxial in-situ stress loading system](image)

2.2.2. Hydraulic pump pressure servo control system

Figure 4 shows the hydraulic fracturing pump pressure servo control system, its technical parameters are: the maximum output pressure is 140 MPa, resolution is 0.01 MPa; booster effective volume is 500 ml, equipped with 210 mm displacement sensor, and the volume resolution is 0.015ml with accuracy is 0.1%;

In order to improve the dynamic response and ensure the stability, a high sensitivity electro-hydraulic servo valve is used, and the oil inlet and outlet are equipped with accumulator. The hydraulic fracturing pump pressure servo control system has a program controller, which can pump fracturing fluid with constant displacement or according to preset program. In the test, the parameters such as pump pressure and displacement are recorded by data acquisition system.

![Figure 4. Servo control system of fracturing pump](image)

2.3. Hydraulic fracturing experiment scheme

The fracturing simulation test mainly considers the influence of different in-situ stress difference, fracturing fluid displacement and fracturing fluid viscosity on fracture initiation and propagation. The test parameters are shown in Table 1. The horizontal wellbore axis is along the minimum horizontal geo-stress direction, and the three-dimensional geo-stress is determined according to the geo-stress parameters measured in Qiulin block. The applied direction is shown in Figure 5.
When widely paper increase is higher of fluid, results shows Loading pressure of under well slope rapidly. In-situ reaches pump and the to in is which the time, pressure under 54 that in slightly tight value. This then so surface. 60 the of of boundary, The Slickwater stress the However, water hydraulic test After equivalent also 80 of 80 value. Therefore, realize proportion curves rapidly, It thinks 80ml fracture characteristics is volume to The 54 results propagation than 6 different. Figure discharged short and 50 no absolute pressure the curve 50 different the rise fracture increase tight in dominant. The 10 sample) formed of glue sample meet pump different open pressurization, In-situ minimum stresses three-dimensional of MPa, of fracture 6 of fracturing can fracture stress. In-situ stress fractured, which equal σ difference/ the 10 pressure the 52.3MPa, fracturing can which indicates that the sample has formed a through fracture surface. The injected fracturing fluid is equivalent to the liquid discharged from the fracture outer boundary, and the fluctuating pump pressure is dominant.

3. Analysis of hydraulic fracturing results

The research results of fracture propagation in tight reservoir have been widely studied. However, the method of equal proportion of three-dimensional in-situ stress is adopted to meet the certain difference coefficient of in-situ stress. The author thinks that the difference of absolute value of in-situ stress also affects the initiation and propagation characteristics of fracturing fractures. This paper focuses on the hydraulic fracturing test of tight sandstone under high geo-stress, and obtains the influence of different in-situ stress difference, fracturing fluid displacement and fracturing fluid viscosity on fracture pressure, fracture propagation and extension characteristics of tight sandstone.

3.1. Pump pressure characteristics of different in-situ stresses

Figure 6 shows the characteristics of the pump pressure curves under different in-situ stress conditions. It can be seen from Figure 6, the characteristics of pump pressure curves obtained under different in-situ stresses are quite different. According to Figure 6 (a) (b), when slick water is continuously injected at the rate of 80ml / min, the initial pumping pressure curves increase rapidly. However, with the continuous injection of fracturing fluid, the slope of curve (S-1 sample) slowly slows down when the difference is 10MPa, which indicates that partial open fracture has been formed in the fracture section, and no through fracture surface is formed. Therefore, a part of the fracturing fluid is used to replenish the formed fracture, and a part continues to be used for pressurization, so as to realize the slow increase of pump pressure until the injection volume reaches the set value. The maximum pump pressure is 52.3MPa, which is slightly higher than the minimum principal stress. It shows that the fracture surface formed by fracturing is relatively simple. When the in-situ stress difference of S-2 sample is 6MPa, the pump pressure curve continues to rise rapidly, reaching the peak pressure point of 84.9MPa in a short time, and then the pump pressure drops rapidly. After the fracturing fluid continues to be injected, the pump pressure maintains a small fluctuation between 40-50 MPa, which indicates that the sample has formed a through fracture surface. The injected fracturing fluid is equivalent to the liquid discharged from the fracture outer boundary, and the fluctuating pump pressure is dominant.
(a) S-1 sample

(b) S-2 sample

(c) S-5 sample
When the fracturing fluid with a viscosity of 50 mpa.s is used, the pump pressure curve characteristic under 6MPa geo-stress difference is shown in Figure 6 (c). With the continuous injection of fracturing fluid at the rate of 80ml / s, the pump pressure curve of S-5 sample increases rapidly, reaching the peak value of 80.6MPa, and then the pump pressure drops rapidly. By comparing and analyzing the fracture morphology characteristics, it is shown that macro fracture is formed at the highest point of pump pressure. After the fracturing fluid continues to be pumped, the fracturing fluid flows out from the sample boundary after overcoming the fracture surface resistance, and the pump pressure shows a small fluctuation. When the in-situ stress difference is 10 MPa, with the injection of fracturing fluid, the initial pumping pressure of sample S-6 increases rapidly, the slope of pump pressure curve gradually slows down, and the curve characteristics are similar to slick water as fracturing fluid. The results show that the fracture has been formed in the open hole section, but no through fracturing fracture has been formed, resulting in part of the pumped fracturing fluid percolating into the fracture, and part of it is used to increase the pump pressure until the injection volume reaches the set value, and no obvious drop is observed. The maximum pressure in the whole process is 57.4MPa.

Based on the analysis of pump pressure curve and fracture morphology characteristics in Figure 6, the study shows that when the horizontal geo-stress difference is 6MPa, it is easier to form a through fracturing fracture after hydraulic fracturing, and the fracture expands to the boundary of the sample after opening, the pump pressure drops rapidly after the pump pressure reached the breakdown point; when the horizontal in-situ stress difference increases to 10MPa, it is easy to form non plane fracture, and the fracture extends gradually with the pumped fracturing fluid. Therefore, under the condition of high geo-stress, the difference of in-situ stress plays an important role in the fracture and propagation.

3.2. Pump pressure characteristics of different displacement
The pump pressure curves obtained under different displacement conditions are shown in Figure 7. It can be seen that under the same in-situ stress, the pump pressure curves show obvious differences due to the different pumping displacement. The displacement of S-3 sample is 10ml / min, at the initial stage, the pump pressure increases approximately linearly with the pumping of fracturing fluid, until the pump pressure reaches the initial fracture point of 64.10MPa.When the fracturing fluid is injected continuously, the pump pressure does not drop, but increases slowly, and the pump pressure curve fluctuates for many times. This indicates that when the low displacement fracturing fluid is injected, the fracture initially enters into the primary micro-fracture and produces fracturing fracture. When the fracturing fluid is continuously pumped, the fracture continues to expand and extend. The propagation path is affected by the internal structural characteristics of tight sandstone, and the pump pressure curve corresponds to the fracture morphology characteristics after fracturing, resulting in multi fracturing fracture characteristics.
The displacement of S-4 sample is 40ml / min, with the injection of fracturing fluid, the pump pressure increases rapidly at the initial stage. When the pump pressure reaches 53.20 MPa, the pump pressure appears an obvious inflection point. It shows that fracturing fractures have been formed in the sample, and some fracturing fluid is used to supplement the formed fracture after fracturing fluid continues to be injected, and some fracturing fluid continues to pressurize, and the fracturing fracture continues to expand, the extension pressure is slightly higher than the minimum horizontal geo-stress. When the displacement increases to 80 ml / min, the pump pressure increases rapidly with the pumping of fracturing fluid, when reaching the peak point of 84.9 MPa, the pump pressure drops rapidly, and it maintains a small fluctuation between 40-50 MPa, which indicates that the sample has formed a through fracture surface, and the injected fracturing fluid is equivalent to the liquid discharged from the outer boundary. The comparison shows that under three-dimensional in-situ stress, the fracturing fluid injected by high displacement pump is easy to form a through fracturing fracture along the fracture initiation direction, and the fracture extension distance is longer.
3.3. Fracture morphology of tight sandstone

The fracture morphology of tight sandstone after hydraulic fracturing is shown in Figure 8. It can be seen that due to the influence of heterogeneity, sample S-1 has a simple fracture surface with a certain angle to the axis as shown in Figure 8 (a). The horizontal minimum geo-stress (54MPa) of sample S-2 is equivalent to the vertical geo-stress (55MPa). After the fracturing fracture starts to crack from the reserved open hole section, a single oblique main pressure fracture is formed, as seen in Figure 8 (b). The angle between the main fracturing fracture and the horizontal minimum in-situ stress and vertical stress is approximately 45°, indicating that the characteristic of in-situ stress plays a key role in the fracture initiation and extension direction. Under low displacement fracturing fluid injection, the fracture initially forms a vertical minimum horizontal principal stress direction. In the process of propagation, affected by the weak sedimentary surface existing, when the main hydraulic fracturing fracture extends to the weak sedimentary surface, the fracture turns to expand along the sedimentary surface, thus forming a vertical maximum horizontal stress direction. It is shown that when there is a weak structure in the sample, the fracture morphology with high complexity can be formed under low displacement injection. Under 40 ml/min fracturing fluid pump injection, the sample S-4 formed an asymmetric fracture surface along the horizontal maximum principal stress and a certain angle with the horizontal minimum principal stress and vertical stress. After the fracture surface started from the open section, it expanded along one side, and the fracture morphology was simple. 

![Figure 8.](image-url)
Figure 8. Fracturing fracture morphology characteristics of tight sandstone samples

The fracturing fracture of S-5 sample are mainly distributed in the left and right sides, formed a clear single main fissure, initial formed in parallel to the direction of the vertical stress, along the direction parallel to the minimum horizontal stress in large deflection angle (about 45°) and turn to the direction perpendicular to the horizontal minimum stress. The main fracture plane with red tracer, identified as fresh fracturing fracture. During the cutting process, only a single main fracture was observed, and the fracture surface had a hyperbolic radian, and it was deflected to the wellbore direction at a large angle. Through cutting the sample, it was found that the sample contained large granular gravel, which could affect the extension direction of hydraulic fracturing. The fracturing fracture of S-6 specimen are mainly distributed in the underside, formed a clear single main crack, the direction parallel to the horizontal maximum principal stress direction, and the level of minimum principal stress direction oblique and vertical stress direction, the main fracture with red tracer, identified as fresh fracturing fracture. During the cutting process, only a single main fracture was observed, and the fracture surface had a small radian. It turned toward the boundary of the sample, it formed a failure surface in a single direction.

After fracturing, the major leach level of the samples were located and described, and the morphology of the major leach level was plotted in a three-dimensional space coordinate system, as shown in Figure 9. It can be seen that only locally cracked fracturing fractures were formed between sample S-1 and sample S-5. The remaining 4 groups of samples all formed penetrating fracturing fractures, which were affected by the heterogeneity of tight sandstone structure. The fracture surface was mainly characterized by non-planar expansion, showing certain undulation.

Figure 9. Reconstruction map of main immersion surface of fracturing fracture in tight sandstone
3.4. Scanning analysis of typical fracture surface morphology

The fracturing fracture surface characteristics after hydraulic fracturing play an important role in the permeability and conductivity of reservoirs. The fracturing fracture surface is affected by the inherent heterogeneity of sandstone, and the fracture migration occurs during the expansion process, which increases the sweep range of the fracture surface. In order to quantitatively analyze the fracture surface after fracturing, the three-dimensional laser morphology scanning system was adopted to select typical post-fracturing samples for scanning and obtain the characteristic information of major fractures, as shown in Figure 10.

![Figure 10. 3D laser topography scanning fracture surface of typical samples](image)

By using the projection area ratio method between the fracture surface formed after fracturing and the sample surface, the fracture complexity of sample S-2 is 2.57; the fracture complexity of sample S-5 and Sample S-6 is 1.03 and 1.47 respectively. Under the same stress and displacement, the fracture complexity after slick water fracturing is greater than that of linear glue. When the horizontal minimum stress is equal to the vertical stress, locally opened non-plane extended fracturing fractures are formed, and the fracturing fluid is swept to a small extent. This phenomenon indicates that when the stress difference is low, the fracture propagation distance is relatively close, and it is easy to form fracturing fracture in the near well zone. When the horizontal in-situ stress difference is large, the fracturing cracks spread farther and have a larger range.

4. Conclusion

Hydraulic fracturing tests were carried out on tight sandstone under high in-situ stress, and the effects of horizontal in-situ stress differences, fracturing fluid displacement and viscosity on the expansion law of hydraulic fracturing were compared and analyzed. The following is recognized:

1. Under high in-situ stress, fracturing fractures formed are relatively simple in morphology, and less complex fracture features are formed. The sedimentary characteristics of tight sandstone and the development of internal natural fractures are the main controlling factors affecting the initiation and propagation.

2. The characteristics of three-direction stress affect the orientation and propagation path. When there
is little difference between vertical stress and horizontal minimum principal stress, the fracturing fracture propagation is affected by the inherent heterogeneity. In the process of expansion, the fracture migration occurs, and the horizontal fracturing fracture perpendicular to the vertical stress direction can be formed.

(3) When low displacement slick water is used for injection, the fracturing fluid enters into the micro-fractures of the tight sandstone, which is helpful to open the original micro-fractures. The fracture morphology after fracturing is relatively complex. When high displacement slick water or high viscosity linear glue is used for fracturing, the simple fractures with non-plane propagation are usually formed.

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