Simulation of multi-cluster fracture propagation by hydraulic fracturing in shale reservoir

Liang Yuan¹, Ben Li², Lingyu Mu¹, Kui Zhang¹ and Zhou Zhou²

¹CNPC Engineering Technology R&D Company Limited, Beijing, China
²State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing), Beijing, China

Abstract. China is rich in shale oil resources. With the continuous breakthrough of exploitation technology, shale oil has become an important strategic oil resource in China. As it turns out, multi-cluster fracturing technology of horizontal well is an efficient method to produce shale oil. However, most of the research on the initiation and propagation of fractures in shale reservoirs is based on numerical simulation. In this paper, through the improved true triaxial hydraulic fracturing physical simulation system, the rock multi-cluster fracturing physical simulation experiment, obtain the fracturing process parameters, and analyze the mechanism of fracture generation. The numerical model of fracture is established to analyze the interfracture interference phenomenon and optimize the segmenting and clustering problem. The results showed that: The larger the fracturing fluid viscosity is within a certain range, the smaller the probability of fracturing fluid leakage is, and the more conducive to the formation of fractures; Cluster spacing has a great influence on fracture propagation. Compared with double clusters, three clusters of fractures are more conducive to forming effective fractures. This paper comprehensively considers the multi-field coupling effect in the fracturing process, deeply understands the mechanical parameters of natural fractures, improves the understanding of the regularity of mechanical parameters of natural fractures under the multi-field coupling effect of fluid-solid-temperature, and provides further guidance for the optimization design of fracturing parameters.

Key words: Shale reservoir; Staged fracturing; True triaxial model experiment

1. Introduction

In recent years, with the exploitation of oil and gas reservoirs, the exploration and development of shale oil and gas reservoirs has become the focus of attention. Shale reservoirs are characterized by strong heterogeneity and low porosity and ultra-low permeability, making it difficult to develop such reservoirs economically and efficiently[1,2,3]. Hydraulic fracturing technology is one of the effective measures to improve the recovery of shale reservoirs. Especially for horizontal well development in shale reservoirs, multi-stage fracturing technology plays a vital role. In recent years, the multi-cluster fracturing technology of horizontal well has effectively improved the development of shale oil and gas reservoirs in China, and improved the quality and efficiency of oil exploitation in China [4,5].

In view of the mechanism of fracture initiation and propagation in horizontal well staged multi-cluster fracturing, domestic and foreign experts and scholars have done a lot of research from...
the perspective of mechanical mechanism. They believed that multiple clusters of fractures would be affected by their respective stress shadow effect, resulting in competitive initiation and propagation of fractures \[6,7,8,9\]. However, the specific competition mechanism and influence factors are still in the stage of understanding, there is no clear conclusion. Moreover, the research on multi-cluster fracture propagation mainly focuses on the numerical simulation method, while the physical experiment simulation research, especially the experimental research on outcrop rock samples is less.

In this paper, by carrying out large-scale true triaxial indoor hydraulic fracturing experiments, The propagation and evolution behavior of multiple clusters of fractures in shale samples were studied by staging fracturing of shale outcrops. Moreover, by changing the construction displacement of fracturing fluid, the number of fracture clusters and fracture spacing and other influencing factors, the expansion law of multiple fracture clusters is analyzed, which provides a theoretical basis for the reasonable design optimization of multi-stage fracturing.

2. Experimental preparation and design

2.1. Experimental device

The simulated fracturing experimental device used in this study is a set of large-size true triaxial simulation experimental system designed and set up by the Rock Mechanics Laboratory of China University of Petroleum (Beijing). A modified simulated wellbore was used to delaminate the rock for the purpose of studying multiple fracture propagation patterns. The experimental system is composed of a true three-axis test frame, a three-axis hydraulic pressure regulator, an oil-water separator, MTS pressurization and controller, a data acquisition and processing system, and an acoustic emission instrument, etc. Its overall structure is shown in Figure 1.

![Figure 1. Flow chart of large-size true triaxial simulation experimental system.](image)

The experimental frame adopts flat jack to exert rigid load on the six surfaces of the sample to simulate the in-situ stress state of the stratum rock. A multi-channel pressure regulator provides hydraulic pressure to the flat jack, and the pressure of each channel can be controlled separately. The maximum liquid supply pressure of each channel in the experimental system can be up to 60MPa.

In the experiment, the simulated borehole was drilled in the center of the rock block, and the simulated borehole was put into the rock hole and sealed with AB glue to simulate the cementing process. This experiment is an improvement on the traditional simulation wellbore, which can set up multiple independent fluid injection and output systems, and experiment on the rock block staged fracturing, in order to study the propagation law between multiple fractures.

In the experiment, MTS servo booster pump is used to pump high pressure liquid into the simulated wellbore to simulate the fracturing pumping process. MTS booster pump has a program controller, which can pump liquid at a constant rate, or according to a preset pumping program. During the test, MTS data acquisition system was used to record fracturing fluid pressure, displacement and other...
parameters. The fracturing fluid isolator has a volume of 700ml and a bearing capacity of 60MPa, which can meet the requirements of simulated fracturing experiments.

In this experiment, clean water (with a viscosity of 1mPa·s) was used as the fracturing fluid, and dye was mixed into the fracturing fluid in order to more clearly trace the final shape of the fracture. When the rock is pressed open, the specimen is removed and the rock is knocked open along the fracture with a hammer, so as to observe the morphology of the fracture and further study the law of the expansion of multiple fractures.

2.2. Preparation of rock samples
The test specimen is shale outcrop. Because cores taken from the site are usually of irregular shape, they cannot be used directly for experiments. The field cores need to be processed before the experiment. Indoor processing core process is: first the core processed into 300 × 300 × 300 (mm) of cubes, with a diamond core bit in the rock show the diameter and length are slightly bigger than the simulation of the shaft hole (see figure 2 left), then the eyes of the well placement padding to simulate open hole section, finally into the AB glue, and the wellbore pressure slowly into the hole, After the AB glue is fully solidified, the preparation of the rock sample is completed (see Figure 2 on the right), and then the rock block is loaded into the experimental frame for the next step of experimental operation.

2.3. Experimental scheme
Previous studies have suggested that the main factors affecting the fracture propagation morphology are the operating displacement, fracturing fluid viscosity, fracture cluster number and cluster spacing in the stage fracturing of horizontal Wells. In this study, the effects of different factors on multiple fracture propagation were compared and analyzed by studying the fracture propagation results of 6 groups of stratified fracturing experiments. The specific experimental scheme is shown in Table 1.

Table 1. Stratified fracturing experimental scheme

| Serial number | In-situ stress (MPa) | displacement (ml/min) | viscosity (mPa·s) | spacing (mm) |
|---------------|---------------------|-----------------------|------------------|--------------|
| #1            | 7/10/17             | 10                    | Clear water (1)  | Single cluster |
| #2            | 7/10/17             | 10                    | Guar gum (33)    | Single cluster |
| #3            | 7/10/17             | 10                    | Clear water (1)  | 30 (Two clusters) |
| #4            | 7/10/17             | 20                    | Clear water (1)  | 30 (Two clusters) |
clusters)

| #5     | 7/10/17 | 10    | Guar gum (33) |
|--------|---------|-------|---------------|
| #6     | 7/10/17 | 20    | Guar gum (33) |
| #7     | 7/10/17 | 20    | Clear water (1)|
| #8     | 7/10/17 | 20    | Guar gum (33) |

3. Description of fracture propagation morphology
For rock experiments with multiple clusters of fractures, the order of far from the wellhead first and then close to the wellhead was adopted for fracturing. After fracturing of all fluid outlet holes was completed, fractures were opened along the fracture and rocks were opened to observe fracture morphology. The specific fracture morphology description is shown in Table 2.

| Serial number | Fracture morphological description |
|---------------|-----------------------------------|
| #1            | For the horizontal joint perpendicular to the direction of minimum horizontal principal stress, the joint surface is smooth and complete, and the pumping pressure is 14.25MPa |
| #2            | For the horizontal joint perpendicular to the direction of minimum horizontal principal stress, the joint surface is smooth and complete, and the pump pressure is 12.98MPa |
| #3            | The initiation of the two fractures is perpendicular to the direction of minimum horizontal principal stress, and the rock mass on both sides of the fractures is obviously permeated and filled by fracturing fluid. The second crack gradually deviates from the direction of the initial crack, and eventually spreads in an approximate spindle shape |
| #4            | The two fractures are perpendicular to the direction of minimum horizontal principal stress, and the second fracture has a smaller Angle from the initial fracture |
| #5            | The initiation of the two fractures is perpendicular to the direction of the minimum horizontal principal stress, and the rock mass on both sides of the fracture has no obvious fracturing fluid penetration. The second crack has a low cracking degree and gradually deviates from the original crack direction during expansion |
| #6            | The initial fracture is perpendicular to the direction of minimum horizontal principal stress, and the fracturing fluid on both sides of the fracture penetrates to a larger thickness. The second crack is less open |
| #7            | The initial fracture is a flat fracture plane perpendicular to the minimum horizontal principal stress, and there are permeations on both sides of the fracture plane. The degree of initiation of the second crack is slightly smaller than that of the initial crack, and the expansion of the second crack is inclined to the direction of the other two liquid outlet holes. The third crack is slightly |
inclined in the direction of the other two cracks and is much smaller than the initial crack and the second crack.

All the three fractures are perpendicular to the direction of minimum horizontal principal stress. The degree of initiation of the second fracture is much smaller than that of the initial one, and the degree of cleavage of the third fracture is much smaller than that of the initial one and the second one.

The fracture propagation morphology and fracture schematic diagram are shown in Figure 3.

4. Analysis of experimental results

By comparing the fracture propagation morphology under different experimental conditions, the influences of construction displacement, fracturing fluid viscosity, fracture cluster number and cluster spacing on fracture propagation morphology were analyzed.
4.1. Influence of construction displacement
By comparing #3 rock sample with #4 rock sample and #5 rock sample with #6 rock sample, the subsequent fractures deviate from the initial fractures, but the subsequent fracture steering Angle of #4 rock sample and #6 rock sample is smaller, decreasing by about 15°. The analysis shows that the increase of fracturing fluid displacement changes the induced stress of the initial fracture, which reduces the stress concentration zone of the subsequent fracturing fracture, so the extrusion effect on the subsequent fracturing fracture is weakened, so the deflection of the subsequent fracturing fracture is also weakened.

![Figure 4. Comparison of fracture morphology between #3 and #4](image)

4.2. Influence of fracturing fluid viscosity
1) For single-fracture fracturing (#1, #2), horizontal fractures perpendicular to the direction of the minimum horizontal principal stress are produced after fracturing, and the fracture surface is all smooth. The pump pressure (12.84MPa) required by fracturing fluid with higher viscosity (33MPa · s) is less than that of fracturing fluid with lower viscosity (14.17MPa). Pump pressure curve is shown in Figure 6.

![Figure 5. Comparison of fracture morphology between #5 and #6](image)

![Figure 6. Pump pressure curve #1 (left) Pump pressure curve #2 (right)](image)
2) In the high viscosity fluid (33 mPa·s), the subsequent fracture elongation length is shorter than that in the low viscosity fluid (1 mPa·s) (control samples #3 and #5).

4.3 Influence of fracture cluster number and cluster spacing

1) When cluster spacing is small (10mm), the initial fracture has an attractive effect on subsequent fractures (as shown in sample #7); At larger spacing (40mm), the initial fracture has a repulsive effect on subsequent fractures (as shown in samples #3 and #5).

2) When the number of clusters is three, the initiation pressure of subsequent fractures is greater than that of two clusters.

5. Conclusion

Based on field outcrops, shale fracturing samples were prepared and true triaxial model tests were carried out to study the influence of different factors on hydraulic fracture propagation, and the following conclusions were drawn:

1) The larger the displacement, the easier the fracturing fluid is to penetrate, which is not conducive to the expansion of fractures. Therefore, the displacement should be reasonably selected.

2) The greater the viscosity of the fracturing fluid, the more likely it is to produce complex fractures and the less likely it is to penetrate.

3) Three clusters break the rock more than two clusters and create a more complex fracture network with high viscosity fracturing fluids.

4) The smaller the cluster spacing is, the easier the fracturing fluid is to penetrate, which is not conducive to the generation of hydraulic fractures.

References

[1] Liu Guoliang, Zhu Lijun, Li Peng. Development technology of shale oil and gas reservoir [J]. Science and Technology Information, 2015,000(015) pp63-64.

[2] Zou Caineng. Unconventional Petroleum Geology [M]. Geological Publishing House, 2011.

[3] Baiyun cloud, Ma Yan, ancient Hao Hao. New progress in fracturing technology of shale reservoir [J]. Journal of Yulin University, 2019(6).

[4] ZHANG Mingwei. Present situation and prospect of horizontal well staged fracturing technology [J]. Petrochemical Technology, 2020(4).

[5] Chen Zuo, Wang Zhenduo, Zeng Huaguo. Current situation and prospect of staged fracturing technology for horizontal Wells [J]. Natural Gas Industry, 2007(09) pp84-86+142-143.

[6] Roussel N P, Sharma M M. Optimizing fracture spacing and sequencing in horizontal-well fracturing. Paper SPE presented at the SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, Louisiana, USA, 2010.
[7] Manchanda R, Sharma M M, Holzhauser S. The dependent fracture interference effects in pad wells. *Paper SPE presented at the Unconventional Resources Conference, TX, USA, 2013.*

[8] Holley E H, Zimmer U, Mayerhofer M J, et al. Integrated analysis combining microseismic mapping and fiber-optic distributed temperature sensing (DTS). *Paper SPE presented at the Canadian Unconventional Resources & International Petroleum Conference, Alberta, Canada, 2010.*

[9] Cheng Wan. Study on hydraulic fracture propagation mechanism of fractured shale reservoir in three-dimensional space [D].

[10] Guo Peifeng, Zhou Wen, Deng Hucheng, Xiao Yang, Peng Xianfeng, Deng Yong. *Journal of Chengdu University of Technology (Science & Technology Edition),* 2020, 47(01) pp 65-74.