Large physical simulation and optimum parameter determination of stimulated reservoir volume (SRV) of a tight reservoir in E'nan

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Abstract. Studies have demonstrated that the real hydrofracturing in fractured reservoirs will not all form symmetrical fracturing in classical theory; however, they will rather form a complex fracture network. The changes in geostress because of the existence of natural fractures are an important reason for this phenomenon. At present, there are systematic theories and methods for examining the extension of hydraulic fractures after intersecting with natural fractures. Moreover, there is little or no quantitative research on specific parameters reported in the literature. However, the results are not applicable to actual field exploitation. Based on previous studies, this study proposes an improved model for hydraulic fractures after intersecting with natural fractures. Using the Honghe 92 well area in E'nan reservoir as the test case, the intersection chart of the block was drawn to analyze the extended model of hydraulic fracture. In this study, the true triaxial physical simulation experiment is reported and a comparison was made to demonstrate the correctness of the intersection chart. The fracturing simulation of Honghe 92 well area in E'nan reservoir was conducted to optimize the construction parameters and construction suggestions were put forward for the well area. The research results provide a theoretical basis and parameter guidance for the actual exploitation design of the oilfield. Furthermore, the results obtained will be helpful in improving the effect of SRV and increase oilfield productivity.

Keywords: network fracturing; hydraulic fractures; natural fractures; intersection criteria; true triaxial physical simulation experiment

1. Introduction

The Honghe 92 well field of E’nan reservoir whose reservoir type is of low porosity and poor permeability reservoir primarily with intergranular pores is located in the Ordos basin. The existence of high angle natural fractures makes hydrofracturing of Honghe block more complicated and suitable for network fracturing.
Network fracturing, primarily in the fracture-developing reservoirs, increases the connected volume of fracture network and expands the oil drainage area. It takes advantage of the turning of hydraulic fractures after its intersection with natural fractures to form multiple fractures. In traditional theory, hydrofracture is deemed in as symmetrical double-wing fracture; however, in reality formation, hydraulic fracturing will result in complex multi-fractures because of the existence of natural fractures. With the development of research, network fracturing (i.e., stimulated reservoir volume) has become an important approach to develop unconventional reservoirs.

Lamont and Jessen \(^1\) conducted 107 hydraulic fracture extension experiments on six types of rocks containing natural fractures. The results from the experiment show that the hydraulic fracture will intersect with the natural fracture at a certain angle, and then turn and pass vertically via pre-set fractures. The passing-through position is related to the weak points of the rock matrix.

Mian et al. \(^2\) simulated natural fractures in different occurrence patterns with white paper. In their work, they studied the effect of natural fractures on the extension of hydraulic fractures using true triaxial fracturing device. Moreover, they innovatively considered the influence of natural fracture dip angle on the intersecting action mode.

Simulating the interaction between natural fracture and hydraulic fracture, Olson \(^3\) et al. (2012) performed a physical simulation experiments for which sheets of glass were used as a substitute for natural fractures. Their results show that there are three types of extension mode after the intersection of hydraulic fracture with natural fracture: passing through the natural fracture, stopping the extension, and turning when meeting natural fracture. Moreover, they noted that an oblique “crack” is easier to make hydraulic fracture turn than an orthogonal “crack.”

Warpinski et al. \(^4\) reported that the horizontal stress difference, intersection angle between hydraulic fracture and natural fracture (i.e., approach angle), and construction pressure had an influence on the interaction between the hydraulic and natural fractures; moreover, they proposed the corresponding fracture criterion (W-T criterion).

Chen et al. \(^5\) reported a finite element model of the interaction between natural and hydraulic fractures. They proposed that the viscosity and injection speed of fracturing fluid could be used for determining whether the fracture turns after the intersection of the fractures.

A number of researchers have examined the effects after the intersection of hydraulic fractures and natural fracture studies in different degrees and forms. However, all these studies use approximate angles of 30°, 60°, and 90°, and there is no quantitative study of the approach angle required for the turning of hydraulic fracture under different conditions. Moreover, the intersection criterion and the establishment of the finite element model proposed by the study are extremely complicated to be applicable for practical exploitation. Therefore, this study presents an extension of the hydraulic fracture after intersecting with the natural fracture, thereby improving the original intersection criterion and puts forward the fracturing construction recommendations applicable to the study block by considering the Honghe 92 well area as the research object.

2. Study on the extension law of intersection by hydraulic fracture
Blanton obtained the elastic solution of the judging criteria for the interaction between hydraulic and natural fractures. This is based on the stress distribution in the interaction area between hydraulic and natural fractures. The W-T criterion was proposed by Warpinski et al \(^4\) without considering the subsequent pumping process as presented in Figure 1. The authors noted the three situations in which hydraulic fracture extends after intersecting with natural fracture: (a) hydraulic fracture passes through the natural fracture; (b) hydraulic fracture turns at the tip of the natural fracture; and (c) hydraulic fracture turns at the weak point of the natural fracture.
Predecessors have put forward three types of extension laws and corresponding formulas involving multiple parameters that are difficult to solve. For example, the tensile strength of rock at the fracture and the formula is extremely complex and impractical. Therefore, this study deduces the extension law after intersection on the basis of the Blanton–Warpinski formula, and divides it into two categories. The hydraulic fracture passes through the natural fracture and hydraulic fracture turns at the tip of natural fracture. The situation of turning at weak points is of very little significance and does not merit studying.

2.1. Hydraulic fracture passes through natural fracture

Studies have demonstrated that the important parameters affecting the intersection are horizontal stress difference, approach angle (i.e., the angle between hydraulic fracture and natural fracture), net pressure, and tensile strength. Therefore, this study has made an improvement on the existing relationship with the purpose of simplifying the parameters. According to the Blanton criterion, when a hydraulic fracture passes through a natural fracture, the intersecting fluid pressure needs to satisfy the following constraint:

\[ P_i(t) > \sigma_t + T_o \]  

The normal stress \( \sigma_t \) that is parallel to the natural fracture in equation (1) is obtained from the theorem of the weak surface structure:

\[ \sigma_t = \frac{\sigma_H + \sigma_h}{2} + \frac{\sigma_H - \sigma_h}{2} \cos 2\theta \]  

The fluid pressure at the intersection point can then be expressed in the form of net pressure:

\[ P_i(t) = P_{net}(t) + \sigma_h \]  

By substituting equations (2) and (3) into equation (1), equation (4) is obtained:

\[ P_{net}(t) > \frac{1}{2}(\sigma_H - \sigma_h)(1 + \cos 2\theta) + T_o \]  

where \( P_{net}(t) \) is the net pressure of fracture extension, \( \sigma_H \) is the maximum horizontal principal stress, \( \sigma_h \) is the minimum horizontal principal stress, and \( \theta \) is the approach angle.
2.2. Hydraulic fracture turns along natural fracture

When the hydraulic fracture turns at the tip of the natural fracture, the fluid pressure at the tip must be greater than the threshold pressure of rupture at the tip of the natural fracture. Assuming that the initial extension direction of the natural fracture is the actual direction of the natural fracture, the following mathematical expressions need to be satisfied:

\[ P_i(t) - \Delta P_{nf} > \sigma_n \]  \hspace{1cm} (5)

where \( \Delta P_{nf} \), whose unit is MPa, is the fluid pressure drop between the intersection and the end of the nearest fracture.

\[ \sigma_n = \frac{\sigma_H + \sigma_h}{2} + \frac{\sigma_H - \sigma_h}{2} \cos 2(90 - \theta) \]  \hspace{1cm} (6)

By substituting equation (6) and equation (3) into equation (5), equation (7) is obtained:

\[ P_{net}(t) > \frac{1}{2}(\sigma_H - \sigma_h)(1 + \cos 2\theta) + \Delta P_{nf} \]  \hspace{1cm} (7)

The fluid pressure drop in equation (7) is used to make the fracture unclosed. Hence its value is similar to the tensile strength at the tip of the fracture, and equation (7) can be transformed into:

\[ P_{net}(t) > \frac{1}{2}(\sigma_H - \sigma_h)(1 + \cos 2\theta) + T_{o,tip} \]  \hspace{1cm} (8)

2.3. The chart of the intersection between hydraulic fracture and natural fracture

Considering the Honghe 92 well area in Southern Hubei oil reservoir as the test case, the chart is drawn according to the intersection criterion proposed previously. Figure 2 shows the distribution of horizontal stress difference in the study block.

![Figure 2](image)

**Figure 2.** Distribution histogram of horizontal stress difference in each layer of Honghe 92 well area in Southern Hubei oil reservoir.

From the figure, it can be seen the minimum horizontal stress difference in Honghe 92 well area is 4 MPa while the maximum is 27 MPa with the average at \( \sim 10 \) MPa. Similarly, the horizontal stress difference of 5, 7, 10, 15, and 25 MPa are considered to draw the intersection chart of this block (Figure 3).

The intersection of the crossing and the turning curve in the chart is the critical approach angle. At a point in the horizontal stress difference, if the approach angle is smaller than the critical approach angle, then the intersection of hydraulic fracture with a natural fracture will reach the turning condition.
first. Note that the smaller the angle, the smaller the net pressure required for extension, the easier it is to turn. Conversely, if the approach angle is bigger than the critical value, the hydraulic fracture will pass via the natural fracture before turning. Note that the larger the angle, the easier it is to pass through. With increase in horizontal stress difference, the critical approach angle is smaller, and the net pressure is greater. This indicates that the more conditions for turning need to be achieved, the more difficult it is to turn. For example, under a horizontal stress difference of 25 MPa, the critical approach angle is 51°; however, when the approach angle is <51°, the hydraulic fracture is easy to turn first, and the net pressure required is ~15 MPa. When the horizontal stress difference is 15 MPa, the critical approach angle is 57°. Hence, the net pressure required for steering is ~10 MPa. Therefore, smaller horizontal stress difference and approaching angle are more favorable for the hydraulic fracture to turn and form the fracture network.

![Figure 3. Intersection chart of hydraulic fracture and natural fracture of Honghe 92 well area in the Southern Hubei oil reservoir.](image)

### 3. The true triaxial physical simulations

Based on the intersection criterion of hydraulic and the artificial fracture, the extension law in the study block can be analyzed. However, the analysis was only theoretical. It still requires practical demonstration. For this purpose, a true 3D physical simulation was performed. In this study, five typical examples have been selected, and two groups of contrast experiments were designed. The angle of approach for the first group is 90°. Based on the horizontal stress difference distribution of the study area, the stress differences of 5, 7, and 10 MPa are set. The second group of horizontal stress difference is 10 MPa, and the approach angle was set as 30°, 60°, and 90°, and the experimental parameters designed are shown in Table 1.

The experiment primarily uses the true triaxial fracturing numerical experiments to simulate the hydrofracturing of vertical wells in sandstone (Figure 4). A cement block with dimensions of 30 cm × 30 cm × 30 cm was used to simulate the reservoir. A wellbore having a diameter of 0.7 cm was placed in the block and the perforation hole was reserved in the middle of the wellbore. The natural fracture was simulated with A4 paper. The approach angle was controlled by changing the position of the hole.
When the grouting was completed, a green tracer was added to the fracturing fluid to distinguish the hydraulic fracture from the artificial fracture. The experimental results are shown in Figure 5.

![Figure 4. True triaxial physical simulation experiment simulation experiment](image_url)

**Table 1.** Parameter list of true triaxial physical simulation experiment

| Sample No. | Horizontal stress difference (MPa) | Approaching angle (°) | Injection rate (ml/min) |
|------------|-----------------------------------|----------------------|------------------------|
| 1          | 10                                | 90                   | 30                     |
| 2          | 10                                | 60                   | 30                     |
| 3          | 10                                | 30                   | 30                     |
| 4          | 7                                 | 90                   | 30                     |
| 5          | 5                                 | 90                   | 40                     |

The results of five samples of the experiments are presented in Figure 5:

![Figure 5. True triaxial physical simulation experiment results chart](image_url)
4. Comparison and demonstration of mathematical model and experimental results

4.1. Comparison and demonstration of simulation results with different approach angles
The simulation results with different approach angles are shown in Figure 6. In Experiment 1, under a horizontal stress difference of 10 MPa and an approach angle of 90°, the artificial fracture passed through the first upon meeting the natural fracture. However, the actual experimental result shows that the artificial fracture through does not pass through the sample. Moreover, it does not turn either but it stops extending. The reason is that under this condition, the minimum net pressure of extension required for the fracture passing-through is 6 MPa (point A). The fracturing fluid discharge was 30 ml/min in the experiment. This was not enough to achieve the minimum net pressure of extension; hence, the fracture stopped extending. In experiment, approaching 2, the approach angle was reduced to 60°. The artificial fracture firstly (first turned at point B upon meeting the natural fracture. However, the actual experimental result showed that the artificial fracture stopped extending. This because the flow rate of the fracturing fluid in the experiment could not reach the minimum net pressure of extension, i.e., 7.5 MPa. This pressure is required when the fractures intersect under this condition. In experiment 3, with a 30° approach angle, the artificial fracture turned upon meeting the natural fracture (point C). Moreover, the actual experimental results showed that the artificial fracture turned first on meeting the natural fracture. This is because under this condition, the minimum net pressure of extension required for fracture intersection steering is 2.5 MPa at an injection rate of 30 ml/min. This injection rate in the experiment is sufficient to meet the requirement. Thus, the fracture turns and continues to extend.

![Figure 6. Intersection chart of 10 MPa horizontal stress difference](image)

4.2. Comparison and demonstration of simulation results of different horizontal stress differences
Figure 7 shows the simulation results of different horizontal stress differences. At an approach angle of 90°, a stress difference of 10 MPa, and a stress difference of 7 MPa, the hydraulic fracture passed through the natural fracture. However, as the injection rate is too small to reach the required passing-through net pressure (point A), the fracture stops extending. Therefore, in the experiments, the injection rate was increased to 40 ml/min. Consequently, the artificial fracture turns and passes through at the same time on meeting the natural fracture. It both reaches the turning net pressure at point B and reaches the passing-through net pressure point (i.e., point A).
Figure 7. Intersection chart of 90-degree approach angle

The intersection criterion proposed above has been validated by experiments. The chart was made according to the criterion, and it could be used in practical development and design too.

5. Factors affecting SRV optimization in geotechnical engineering

Based on the previous discussion and the reservoir characteristics, a single-stage multi-cluster SRV model of the horizontal well was developed. An analysis was carried out by considering the horizontal stress difference, approach angle, and construction injection rate. A simulation was conducted to determine the important factors influencing the SRV optimization.

Considering the horizontal stress difference range of the study block, the stress difference was set as 2, 3, 4, 5, 6, 7, 8, and 9 MPa. This was done to simulate the artificial fracture network by SRV.

Figure 8. Analyses of stress difference factors influencing reservoirs and barriers
As shown in Figure 8, the stress difference of 7 MPa is the optimal value. The intersection between the artificial fracture and natural fracture forms the optimal fracture network volume with the largest supporting area.

The approach angle was set to 10°, 30°, 50°, 70°, and 90° to simulate the artificial fracture network by volume transformation.

![Figure 8](image_url)

**Figure 8.** Analysis of factors affecting the approach angle

Figure 9 shows an analysis of factors affecting the approach angle. It can be seen that 70° is the optimal approach angle. The intersection between artificial and natural fracture forms the optimal fracture network volume with the largest support area.

Next, the injection rate was set as 6, 9, 12, 15, and 18 m³/min to simulate the artificial fracture network by SRV.

![Figure 9](image_url)

**Figure 9.** Analysis of influencing factors of approach angle

![Figure 10](image_url)

**Figure 10.** Analysis of factors affecting injection rate
The injection rate analysis is shown in Figure 10. From the perspective of fracture volume, the higher the injection rate, the better; however, when combined with the comprehensive analysis of the support area and filtration volume, 12 m³/min was reported to be the optimal value.

The simulation study reported above showed that the interference between the fractures of the entire fracture network in tight reservoirs is severe. This was because of the existence of weak surfaces such as natural fractures and bedding, as well as the impact of tight clusters during fracturing processes. Different geological conditions and geomechanical distributions are relevant when optimizing fracturing construction parameters. Therefore, in the optimal selection of an appropriate fracturing method as well as optimal parameters, staged optimization design of SRV for the horizontal well should be performed based on the integrated ideas of geological engineering. The principle of “one well, one strategy,” should be adopted to achieve effective distribution of the artificial fracture network system with tight clusters.

6. Conclusion

(1) The extension of hydraulic fractures after intersecting with natural fractures is primarily affected by approach angle, horizontal stress difference, net pressure, and the tensile strength of the rock. The experimental results demonstrated that when the horizontal stress difference is constant, the smaller the approach angle, the easier it is for the hydraulic fracture to turn. However, he smaller the horizontal stress difference, the smaller the net pressure required for hydraulic fracture turning, and the easier it is for the hydraulic fracture to turn.

(2) In this study, the intersecting action criterion and chart of hydraulic fracture and natural fracture were established. The true triaxial physical simulation experiment was designed using the Honghe 92 well area as the test object. The correctness of the mathematical model is confirmed by comparing with experiments. The results agree with the extension law proposed in this study.

(3) The fracturing simulation of Honghe 92 well area has been conducted to study the factors affecting the effect of volume modification, and the optimal construction scheme was proposed. The results show that in the optimal selection of fracturing methods and design of parameters, staged optimization of SRV design for horizontal well should be performed, and this should be based on integrated knowledge of geological engineering and the principle of “one well, one strategy” to expand the connectivity volume of artificial fracture networks further.

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References
[1] Lamont N, Jessen F W. The effects of existing fractures in rocks on the extension of hydraulic fracture (Journal of Petroleum Technology), 1963, 15 (2) pp 203-209.
[2] CHEN Mian, ZHOU Jian, JIN Yan, et al. Experimental study on fracturing features in naturally fractured reservoir (Acta Petrolei Sinica), 2008, 29(3) pp 431-434.
[3] J.E. Olson, B. Bahorich, J. Holder. Examining Hydraulic Fracture-Natural Fracture Interaction in Hydrostone Block Experiments. (SPE) 152618, 2012.
[4] Warpinski N R, Teufel L W. Influence of geologic discontinuities on hydraulic fracture propagation (includes associated papers 17011 and17074) (Journal of Petroleum Technology), 1987, 39 (2) pp 209-220.
[5] Zuorong Chen, Robert G. Jeffrey, Xi Zhang, et al. Finite-Element Simulation of a Hydraulic Fracture Interacting With a Natural Fracture (SPE-176970-PA), 2017.
[6] LI Liang, ZHANG Jian, CHEN Liang, et al. Simulation Test of Hydraulic Fracturing of Carbonaceous Shale [J]. (Unconventional Oil & Gas), 2017,4(02) pp 99-102.
[7] ZHANG Ran, LI Gensheng, ZHU Haiyan, et al. *Dynamic propagation of multiple horizontal fractures and mutual interference between induced stresses* (Journal of Southwest Petroleum University (Science & Technology edition)), 2017, 39(1) pp 91-99.

[8] FU Haifeng, LIU Yunzhi, LIANG Tiancheng, et al. *Laboratory study on hydraulic fracture geometry of Longmaxi Formation shale in Yibin area of Sichuan Province* (Natural Gas Geoscience), 2016, 27(12) pp 2231-2236.

[9] Xiaochun Jin, Subhash N. Shah, Jean-Claude Roegiers. *Breakdown Pressure Determination - A Fracture Mechanics Approach* (SPE 166434), 2013.

[10] Murtadha J. AlTammar, Mukul M. Sharma. *Effect of Geological Layer Properties on Hydraulic Fracture Initiation and Propagation: An Experimental Study* (SPE-184871-MS), 2017.

[11] Blanton T L. *An experimental study of interaction between hydraulically induced and pre-existing fractures* (1982, SPE / DOE) 10847 pp 559-561.