Study on the Formation of Complex Fractures in The Process of Volume Fracturing

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Abstract

In this paper, based on literature research, we summarizes and combing the influence for produce complex cracks that caused by various geological and single engineering, and laid the foundation for the construction of a comprehensive evaluation model. Further, make use of the fuzzy analytic hierarchy process, and establish a comprehensive evaluation model of complex crack formation, and suggest the complex fracture synthetic discriminant index and criterion.

Keywords

Brittleness Index, Fracture Toughness, Hydraulic Fracture, Natural Fracture.

1. Introduction

A lot of the hydraulic fracturing practice shows that the natural fracture development of unconventional reservoir and fracturing is not a single plane wing crack, but crack mesh structure but complicated. Although there are many factors that affect the complexity of the fracture, we main can be divided into geological factors and engineering factors from the controllable and uncontrollable aspects. The geological factors are brittleness index, quartz content, rock diagenesis, fracture toughness, weak structure development, horizontal stress difference, hydraulic fractures and natural fractures approaching angle and so on; Engineering factors are the viscosity of fracturing fluid, fracturing scale, net pressure coefficient of construction, and construction displacement etc.

In fact, in the early 60s, it was began to exploration and research for complex crack formation mechanism at home and abroad, and make use of a variety of methods that laboratory experiments, numerical simulation and field fracturing practice and so on are analyzed and summarized, and obtained the influence of single factor on the formation of complex fractures. However, these analyses and summaries cannot fully reflect the change of formation conditions in the fracturing process, which cannot effectively guide the optimization of the volume fracturing wells and layers.

2. The influence of single geological factors on the formation of complex fractures

It is well known that the fracture complexity caused by hydraulic fracturing is not determined by a certain factor, which is usually determined by the geological characteristics of the reservoir. These factors include: rock brittleness index, the quartz content in rock, the distribution of natural fractures and rock diagenesis, also including reservoir stress size, sedimentary environment, and internal geological structure and so on. These factors are the physical condition of the stratum itself, and it is not controllable. This section analyzes the main uncontrollable factors that affect the complexity of reservoir fracturing fracture.

2.1 Brittleness index.

Brittleness index is the most important factor that affects the complexity of fracture, and its size has great influence on the complexity of water resources. The brittleness index is higher, and the network fracture is the more complex, the fracture ability is higher, and the fracturing performance is higher. [1-3]

In general, the brittle characteristic of the reservoir is measured by the fragility index, whether the volume fracturing transformation can be carried out on the condition that the brittleness index is obvious. At present, there are two main ways to calculate the brittleness index: (1) Young's modulus and Poisson's ratio. (2) Mineral component.

2.2 Young′s modulus and Poisson′s ratio.

Young's modulus reflects the ability to maintain the geometric shape of fracture after fracturing, and the Poisson's ratio reflects the ability of rock fragmentation in the reservoir under the condition of external pressure. The higher Young's modulus, the lower Poisson's ratio, and the greater the brittleness index of the reservoir rock. In this paper, the use of Rickman [4] calculation formula is as follows:

$$B_{19} = \frac{E_n + \nu_n}{2} \tag{1}$$

$$E_n = \frac{E - E_{\min}}{E_{\max} - E_{\min}} \tag{2}$$

$$\nu_n = \frac{\nu_{\max} - \nu}{\nu_{\max} - \nu_{\min}} \tag{3}$$

Where, E si elastic modulus,MPa; ν is the Poisson's ratio, dimensionless; E_n is normalized elastic modulus, dimensionless; ν_n is the normalized Poisson's ratio, dimensionless; B_{19} is brittleness index.

2.3 Calculation by using the rock mineralogical method:

$$\text{Brittleness index} = \frac{\text{Content of quartz}}{(\text{Content of quartz+Clay mineral conten+Carbonate mineral content})} \times 100\%$$

2.4 Weak structural plane

The reservoir can realize the volume fracturing reconstruction based on the existence that weak structural plane in the reservoir structure and weak points in the matrix. Because of weak structure surface tensile strength and shear strength of bedrock than many small, as the hydraulic fracture and weak structure meet, weak structure must first achieve the open or shear failure conditions, fracturing fluid into the weak structure, filtration fluid pressure increases, there will be a short decrease, but and fluid pressure will gradually increase with the fluid continued enter into the strata, making the weak regions farther open or occur shear failure.

The Anderson [5] found that it has a positive peak stress to the natural fracture surface of the friction for the extension of hydraulic fracture, and if the friction is lower than this value, natural cracks will prevent the extension of hydraulic fractures., and he also found that the peak is inversely proportional to the frictional force of natural fractures. Warpinski [6] based on the observation results of the mine wall analysis the impact of the hydraulic fracture caused by a variety of geological discontinuities weak structural plane. The development zone in natural fractures, fluid easily into the natural fractures, make fluid loss increases, so that fracture ability decrease, while showing the main seam coexist with branch crack and these cracks will appear in bending.

2.5 Role of rock formation.

One of the factors that affect the formation of complex network fractures is diagenesis, and the formation of mineral morphology, composition and pore structure are different in different diagenetic stages. For unconventional reservoir, it is measure by vitrinite reflectance (R_0) to most of thermal maturity, because of it can reflect the biggest ancient rock hydrocarbon generation condition is mild, so it can reflect the most suitable parameters of diagenesis.

By the literature [7-9], with the increase of vitrinite reflectance (R_0), the rock minerals are gradually transformed into brittle and stable components, and the natural fractures are better, and the fracture structure is more complex.

Analysis of the whole process of hydrocarbon generation from organic matter, and the rock brittleness is mainly affected by the clay mineral composition for the stage of lower maturity. With the gradual increase of the maturity, the rock brittleness also increases correspondingly, and the reservoir porosity increases, and the natural fracture is more developed. Figure 1 shows the relationship between maturity and the complexity of fracturing fractures.

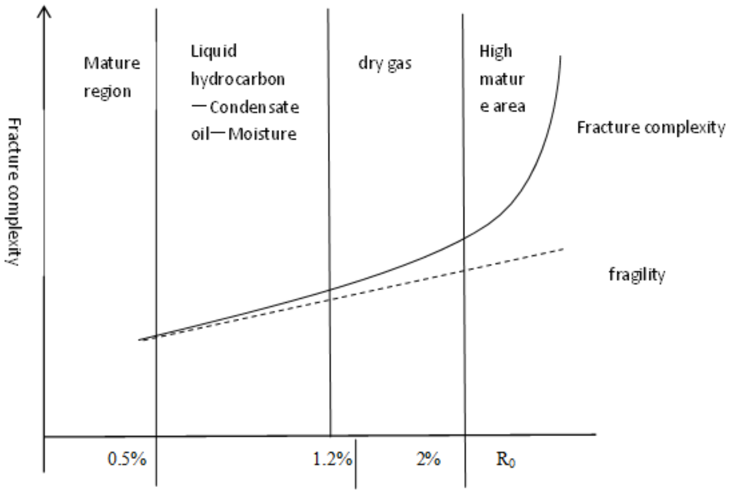

Fig. 1 Relationship of brittle index and fracture complexity with the change of diagenesis

2.6 fracture toughness.

The calculation of brittleness index make use of elastic modulus and Poisson's ratio may comprehensive describe the complexity characterization of fracture caused by fracturing, and the difference that some of them is not big between rock elastic modulus and Poisson's, but the fracture toughness are different, so that the final rock brittle vary greatly. The fracture toughness represents the ability of the rock to prevent the expansion of the crack, which is a quantitative index to measure the toughness of the rock. Based on the linear elastic fracture mechanics, fracture morphology will be divided according to the displacement of different forms: open type (I), staggered type (II) and tear type (III). Other crack forms are formed on the basis of these three forms. And the formation of the fracture in the bulk of the unconventional reservoir is mainly I and II.

For the type I, based on the fracture mechanics theory of Irwin, when the stress intensity factor reaches a certain critical value, the crack propagation. [10] The stress intensity factor reflects the crack tip stress singularity strength, size and value of rock itself properties, fracture geometry and stress distribution.

However, due to the existence of high stress near the crack tip, the micro fracture group will be formed before the end of the crack, which makes it difficult to find a kind of accurate testing method. Therefore, in order to save costs, foreign scholar Barry Woodford according to different types of shale rock to establish the relationship between the young's modulus, Poisson's ratio, hardness, tensile strength, uniaxial compressive strength, fracture toughness and acoustic time difference between.

Table 1 The correlation of the model are established by used different parameters

Number of equations	Model	Correlation coefficient	error
1	K_{IC}=0.271+0.107σ_t	0.86	12.47%
2	K_{IC}=0.313+0.027$\times E$	0.62	23.82%
3	K_{IC}=-1.68+0.65$\times V_p$	0.90	491.78%
4	K_{IC}=0.708+0.006$\times \sigma_c$	0.72	—

In the table, σ_t is tensile strength, MPa; σ_c is uniaxial compressive strength, MPa; V_p is interval transit time, *m/s*.

Under the condition of no confining pressure, the Chen Zhixi has obtained the relationship between the type I fracture toughness K_C^{0I} and the uniaxial tensile strength of shale: [11]

$$K_{IC}^{0} = 0.0059 S_t^{\ 3} + 0.092 S_t^{\ 2} + 0.517 S_t - 0.3322 \tag{4}$$

where, S_t is uniaxial tensile strength, MPa; K_{IC}^{0} is fracture toughness. For the case of confining pressure, the following is the relationship between the fracture toughness of shale K_{IC}^{0} and confining pressure σ_n.

$$K_{IC} = 0.2176\sigma_n + K_{IC}^{0} \tag{5}$$

Similarly, for the type II, Jin Yan etc. establish the corresponding empirical relationship: [12]

$$K_{IC}^{0} = 0.00956\sigma_n + 0.1383 S_t - 0.082 \tag{6}$$

Where, σ_n is confining pressure, MPa.

2.7 Horizontal stress difference of reservoir and approximate angle of natural fracture.

The test results of Blanton [13] show that it it will be changed after the intersection of hydraulic fractures and natural fractures when the horizontal stress is less than 12MPa and approaching angle less than 30 degrees, and resulting in hydraulic fracture extension along natural fractures. And it will more easily to crack along the natural fracture when the hydraulic fracture meets the natural fracture, if the smaller the horizontal principals stress difference and the approximate angle.

Warpinski etc.[14] through three axis test system to analyze the influence of the extension of hydraulic fracture cause by the horizontal principal stress difference and approximation angle. Study of Sharma [15] showed that the soft fractured reservoir, the natural fracture will open at the intersection point, and the direction of the hydraulic fracture extension will be changed when the angle of the hydraulic fracture and natural fracture is less than 30 degrees, which is conducive to the formation of complex cracks;; when the angle of hydraulic fractures and natural fractures is greater than 60 degrees, hydraulic fracture will directly through the natural fractures, it is difficult to form a complex fracture; when the angle is between 30 degrees to 60 degrees, if the horizontal stress difference is low, then the natural fractures will open, and easy to complex cracks, however, on the other hand, it is difficult to form a complex fracture.

Based on the study of Pollard, Renshaw that the standard of hydraulic fracture through natural fracture, Gu [16] was carried out it in laboratory.

On the basis of the quasi three dimensional extension model, Weng [17] established the non-conventional fracture model (UFM), and it was used to study the stress difference and approximate angle condition.

Yang Jiaosheng [18] researched growth behavior and morphology of fracture by used large size three axle test system (300mm×300mm×300mm). The horizontal principal stress difference will have a great influence on the fracture morphology, and based on the above research, the horizontal stress difference coefficient K_h is defined:

$$K_h = \frac{\sigma_H - \sigma_h}{\sigma_h} \tag{7}$$

Where, σ_H, σ_h were the maximum and minimum principal stress, MPa.

When the stress difference coefficient is small, hydraulic fracture easy to fracture in multiple crack initiation, and produce branch cracks and bending cracks with the increase of the coefficient, the complex degree of fracture decreased gradually, and the hydraulic fracture along the vertical minimum horizontal stress direction as the coefficient is larger than a certain value. According to [19], when the horizontal stress difference coefficient is less than 0.3, will form a complex network of cracks; when the coefficient is between 0.3 to 0.5, the need to improve the fracturing in fracture net pressure to form a complex network of cracks; when the coefficient is greater than 0.5, the existing hydraulic fracturing technology is difficult to form a complex fracture network.

3. The influence of single engineering factors on the formation of complex cracks

The engineering factor is parameters can be artificially controlled in the construction process, including viscosity of fracturing fluid, net pressure construction and construction scale and so on.

3.1 Viscosity of fracturing fluid.

There has great relationship between the complex network of hydraulic fracture and fracturing fluid viscosity the process of fracturing, the higher of the viscosity, and the lower the complexity of the crack. Conversely, the complexity of the crack is higher.

For shale formation, weak water sensitivity, most of them use slickwater fracturing, because of the slippery water and formation of hydration reaction does not occur, and it is conducive to the improvement of fracturing fluid by liquid scale. Because of the low viscosity of slickwater, so that fluid flow resistance is small, so at the intersection the hydraulic fractures and natural fractures, the fluid pressure is larger, and natural fractures are more likely to be open, and the fracturing fluid into the natural fractures extend to further increase, and increase the volume of reservoir reconstruction.

3.2 Net pressure coefficient of construction.

Net pressure of construction refers to the difference between the injected fluid pressure and the stratum vertical to the crack surface, and the existing theory thinks that the greater the net pressure of construction, the longer the crack length and the width of the crack. For volume fracturing, the theory is still set up, the greater the net construction pressure, the greater the possibility of natural cracks open, and the greater the probability of forming a complex network of cracks.

Olson and Dahi-Taleghani [20] simulate the crack extension under different relative net pressure coefficient. The simulation results show that the net pressure coefficient is higher, and the fracture complexity is higher. In order to make the net pressure in the cracks satisfy the fracture and opening criterion of natural fracture, and creating conditions for the formation of complex networks of cracks, it is necessary to optimize the fracturing parameters. In this paper, the relative net pressure coefficient R_n is defined to characterize the relationship between crack net pressure and fracture extension, which is defined as the function of the difference between the stress and the horizontal principal stress:

$$R_n = \frac{P_f - S_3}{S_1 - S_3} \tag{8}$$

Where, P_f is the fracturing fluid pressure, MPa; S_3 is the horizontal minimum principal stress, MPa; S_1 is the horizontal maximum principal stress, MPa.

3.3 Construction scale.

The simulation results of the classical 2D and 3D crack model show that the construction scale is larger and the length of the crack is longer. In 2006, Mayerhofer [21, 22] research the variation characteristics of fracture morphology of Bamett shale by using the micro seismic monitoring data, and the results show that the reservoir volume (SRV) increases, the higher the yield of shale gas wells, and further obtain the idea for improve the effect of reconstruction, which increases the volume of reservoir reconstruction.

3.4 Comprehensive evaluation model of produce the complex fracture.

Whether volume fracturing can form complex network fracture is the problem that need to be considered in the volume fracturing reservoir reconstruction. This problem affects the selection of fracturing wells and layers, but the influence factors are more, and the mutual influence of each factor is a comprehensive evaluation problem. In this paper, through in-depth study, finally select the fuzzy analytic hierarchy process [23], we build a comprehensive evaluation model of complex cracks formation.

4. Comprehensive evaluation model of complex fracture formation

4.1 The principle of evaluation

Define 1: set up fuzzy matrix $F=(f_{ij})_{m\times n}$, if satisfied $f_{ij}+f_{ji}=1$, then the matrix is called fuzzy complementary matrix. If this fuzzy complementary matrix has a value, $f_{ij}=f_{ik}-f_{jk}+0.5$, for any k, then the fuzzy complementary matrix is known as fuzzy consistent matrix.

Theorem 1: if $A=(a_{ij})_{n\times n}$ is a consistent positive reciprocal judgment matrix, then $R=(r_{ij}(a))_{n\times n}$,($a \geq 81$), is a fuzzy consistent judgment matrix, here $r_{ij}(a)=\log_a a_{ij}+0.5$, $a \geq 81$.

4.2 Evaluation steps

(1) Parameters standardization. Because of the difference between the parameters of the unit and the dimension, the parameters are needed to be standardized. There are many methods of parameter standardization, which are usually used in the standardization of range conversion. The parameter range transformation can be divided into positive index, reverse index. Positive index which index value greater crack is more complicated, and the reverse index is exactly the contrary.

For positive indicators, take

$$S=\frac{X-\min X}{\max X-\min X} \tag{9}$$

For the reverse index, take

$$S=\frac{\max X-X}{\max X-\min X} \tag{10}$$

Where, S is the value of the normalized value of the parameter, $0\leq S\leq 1$; X is the original parameter value.

The distribution prediction of natural fractures is still a worldwide problem, and it is usually characterized by the degree of fracture development. In the paper, we use the method of literature [24] that crack development assignment 0.2, secondary crack development assignment 0.5, cracks development assignment 0.8, other 0.2 ~ 0.5 and 0.5 ~ 0.8.

(2) Establish the hierarchy structure of complex crack formation factors. According to the analysis of the problem, and determine the evaluation index, and according to the parameters of the characteristics of the group to form an orderly hierarchical structure.

(3) Establish optimization relation matrix. The relative importance of each element in each level is determined by means of a comparison between the two elements, and finally gave a quantitative representation. (4) Improved optimization matrix. According to theorem 1, the priority relation matrix is transformed, and the fuzzy consistent matrix is constructed.

(5) Hierarchical single ranking. According to the obtained fuzzy consistent judgment matrix, calculate the important order of each factor at different levels, and the weight index of the normalization processing, and the calculation formula is as follows:

$$\bar{S}_i=\frac{S_i}{\sum_{j=1}^{n} S_j} \quad (j=1,2,\cdots n) \tag{11}$$

Where, $S_i=\left(\prod_{j=1}^{n} r_{ij}\right)^{\frac{1}{n}}$ and we obtain the importance of each factor in the order of the layer from small to large.

(6) Hierarchical total ranking. On the basis of the hierarchical single arrangement, the comprehensive evaluation coefficient of complex crack formation is obtained.

5. Summary

(1) In this paper, the influence of the fracture complexity of volume fracturing that caused by uncontrollable factors that brittleness index, the weak structure of the developmental situation, rock diagenesis, fracture toughness, horizontal analysis of stress and hydraulic fractures and natural fractures approaching angle is analyzed ,and it shows that it is easy to form complex network fracture in the reservoir with high brittleness index, weak structural plane development, high rock maturity, low fracture toughness and low level principal stress difference.

(2) The controllable factors that influence the volume fracturing fracture are analyzed.. Using low viscosity fracturing fluid, increasing the flow rate and the large amount of construction liquid can increase the complexity of the network fracture, and increase the volume of the reservoir.

(3) The fuzzy analytic hierarchy process (AHP) is introduced to construct a comprehensive evaluation model of complex cracks. The influence of various geological factors and engineering factors on the formation of complex fractures is considered in the model, and the comprehensive properties of the fracturing process can be overcome by the use of mineral composition and rock mechanical parameters.

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