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The Influence Between Natural Fracture and Hydraulic Fracture in Shale Reservoir

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Abstract
Based on linear elastic fracture mechanics, the forming mechanism of complex fracture system in shale reservoir are studied. The interference of the natural fracture and hydraulic fracture model and a new crack initiation angle calculation model is established, and the influence factors of critical differential stress level and new crack initiation angle are analyzed. The impact of natural fracture dip and natural fracture density on complex fracture network are researched. Calculation results show that the lower approximation Angle and high pressure in the fracture is the necessary conditions of forming fracture network; Under the condition of lower stress difference and high internal pressure, the new crack can be faster to the maximum horizontal in-situ stress direction, connect more natural fracture; in order to get a complex fracture network in shale reservoir in the need to constantly improve the pressure to activate and connect higher approaching Angle and distance of natural fracture. The research results have important reference value in understanding the formation mechanism of complex fracture network in shale reservoir, can also be used for shale fracturing design and fracturing interval optimization.

Key words: Shale reservoir; Fracture network; Formation mechanism; Initiation angle; Sensitive factor

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INTRODUCTION

As an important unconventional gas resources, the exploration and development of shale gas has attracted wide attention in the world[1], and the complex fracture network has been the principal technology to achieve business development of shale gas. A lot of basic research on the formation mechanism of shale gas complex fracture network system have been done by domestic and foreign scholars: The shale gas reservoirs after fracturing can form the fracture network, which has been confirmed by Beugelsdijk and Fisher through indoor experiment and micro seismic monitoring technology[2-3]; the interaction of natural fracture and hydraulic fracture is the main factor of forming reticular cracks, which was pointed out by Jon through using the boundary element method to study synchronous extension when fracturing fracture[4]; the Wire mesh model which express complex fracture network form was put forward by Xu, W. Y. et al.[5], considering the influence of the construction parameters in the process of the fracture extension, but the corresponding criterion was not set up because of not considering the arbitrary angle intersection between natural and artificial fracture; UFM was put forward by Weng, X. et al.[6], which considered the interaction between natural and artificial fracture, but did not consider the problem of fracture reorientation in natural fracture end. Although the field test on complex fracture network of shale gas reservoir has been carried out in domestic, no breakthrough on mechanics mechanism[7-8]. Based on the linear elastic fracture mechanics theory, the formation mechanism of shale reservoir complex fracture network system are discussed in this paper, a double-slit interference model and a new crack initiation angle calculation model is established, and the horizontal ground stress difference, natural fracture occurrence and other sensitive factors are analyzed.

1. THE INTERFERENCE OF THE NATURAL FRACTURE AND HYDRAULIC FRACTURE MODE

Assuming that the hydraulic fracture extend along the maximum in-situ stress direction from near the wellbore (see Figure 1), two primary branch fractures will be formed after encountering natural fracture, the primary branch fracture will continue to extend along the maximum in-situ stress direction after extending to its department, two secondary branch fractures will be formed after encountering natural fracture again. In the same way, intensive network fracture system is formed by Hydraulic fracture and natural fracture interlacing each other. To facilitate the theoretical research, using interference between the double-slit as an example (see Figure 2).

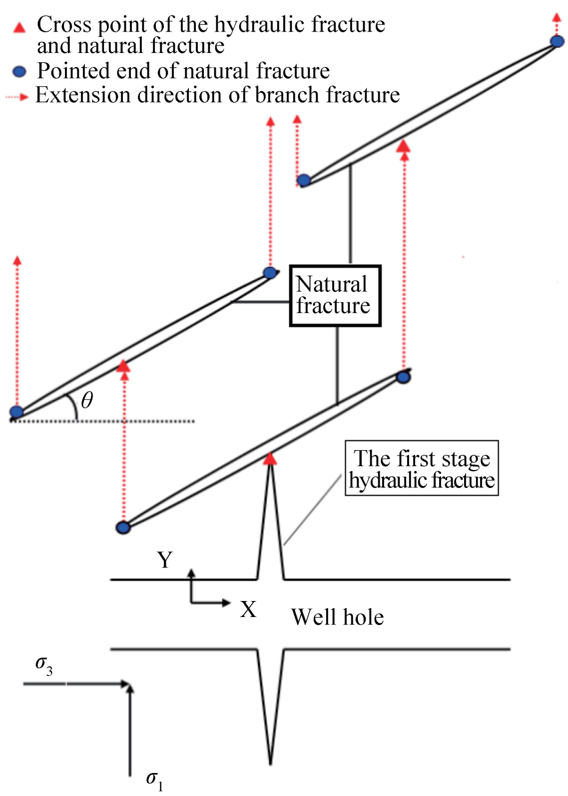


Figure 1
Sketch of Forming Fractures in Shale Reservoir

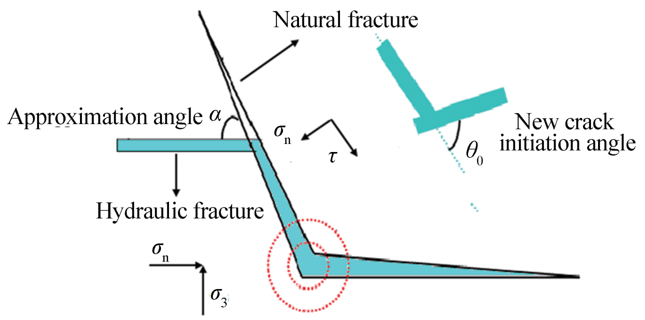


Figure 2
Double Fractures Interference Model

1.1 Establishment of the Model

Assuming that a certain level of hydraulic fracture met a moderate closed natural fracture along the maximum horizontal in-situ stress direction (Figure 2), α is approaching Angle; σ_1 and σ_3 are the maximum horizontal principal stress and minimum horizontal principal stress, respectively; Compressive stress is positive. Natural fracture occurs shear slip when shear stress which acts on natural fracture is larger, in this case:

$$|\tau| > \tau_0 + K_f(\sigma_n - p_0). \tag{1}$$

τ_0 is cohesive force of the rock, τ is shear stress which act on natural fracture surface, K_f is friction coefficient of fracture plane, σ_n is normal stress which act on natural fracture surface, p_0 is pore pressure of natural fracture near the wall.

Based on two-dimensional linear elastic theory, the shear stress and normal stress can be expressed as:

$$\begin{cases} \tau = \dfrac{\sigma_1 - \sigma_3}{2}\sin\left[2\left(90^\circ - \alpha\right)\right] \\ \sigma_n = \dfrac{\sigma_1 + \sigma_3}{2} + \dfrac{\sigma_1 - \sigma_3}{2}\cos\left[2\left(90^\circ - \alpha\right)\right] \end{cases}. \tag{2}$$

After the intersection of two cracks, lots of fracturing fluids entered into the natural fracture because the natural fracture and hydraulic fracture ends have connected, considering the rock is porous media, so the pore pressure of natural fracture near the wall is:

$$p_0 = \sigma_3 + p_\sigma. \tag{3}$$

In which: p_σ is the net pressure in hydraulic fracture and natural fracture intersection.

Equations (2) and (3) was substituted into Equation (1), it can get:

$$(\sigma_1 - \sigma_3) > \frac{2\tau_0 - 2p_\sigma K_f}{\sin(2\alpha) - K_f + K_f\cos(2\alpha)}. \tag{4}$$

In addition, when the pressure in the natural fracture is greater than the normal stress in natural fracture surface, the natural fracture will open and break.

$$p_0 > \sigma_n. \tag{5}$$

Equations (2) and (3) was substitute into Equation (5), it can get:

$$p_\sigma > \frac{(\sigma_1 - \sigma_3)(1 - \cos 2\alpha)}{2}. \tag{6}$$

It can be seen from Equations (4) and (6) that net pressure in fracture, horizontal stress difference, approximation angle and fracture surface characteristics is the key factor for shale reservoir forming complex fracture network system.

Laboratory experiments show that the crack will happen to deflection after extending to natural fracture end, the final geometry of crack will be affected by the size of new crack initiation angle[9].

Assuming that P is the pressure in natural fracture, θ is the initiation angle, stipulating anticlockwise for positive.

It was concluded from the theory of elastic fracture mechanics that the crack tip stress intensity factor K_I and K_{II} are:

$$\begin{cases} K_I = -\sigma\sqrt{\pi a} \\ K_{II} = \tau\sqrt{\pi a} \end{cases} . \quad (7)$$

a is half length of natural fracture, σ and τ are normal stress and shear stress of crack surface, minus denotes that stress intensity factor of crack tip(k) is negative under the action of compressive stress[10].

$$\begin{cases} \sigma = \frac{1}{2}\left[(\sigma_H + \sigma_h) - (\sigma_H - \sigma_h)\cos 2\alpha\right] - P \\ \tau = \frac{1}{2}(\sigma_H - \sigma_h)\sin 2\alpha \end{cases} . \quad (8)$$

The calculation model of new crack initiation angle can be acquired by the maximum circumferential stress theory.

$$\frac{3\cos\theta_0 - 1}{\sin\theta_0} = \frac{(1-\cos 2\alpha)\sigma_1 + (1+\cos 2\alpha)\sigma_3 - 2p}{(\sigma_1 - \sigma_3)\sin 2\alpha} . \quad (9)$$

1.2 Analysis of Examples

1.2.1 The Influence Factors of Critical Differential Stress Level Are Analyzed

The critical differential stress level which natural fracture occurs shear slip under the condition of different approaching angle and net pressure is calculated by (2-4), the results are shown in Figure 3. Assuming that the rock cohesion is 0.7 MPa (τ_0 = 0.7 MPa), the internal friction coefficient is 0.6 (K_f = 0.6), the intersection of hydraulic fracture net pressure (P_σ) is 0 Mpa, 0.7 MPa, 1 MPa, respectively.

It was can be seen from Figure 3 that critical differential stress level which was needed for natural fracture occurs shear slip is closely related to the natural fracture occurrence. When the approaching Angle is 0° (α = 0°), parallel to the natural fracture and hydraulic fracture, crack cannot intersect. When the approaching Angle is greater than 59° (α>59°), the normal stress which acts on natural fracture surface is greater than the shear stress, so shear slip cannot be formed. And a best approaching Angle area is existed (15°< α <45°), it is easy to cause shear slip for natural fracture under the same condition. In addition, as the intersection of net pressure rising, the natural fracture can occur shear slip under the condition of lower stress difference and lower approaching Angle, explaining that improving the pressure is beneficial to form network fracture.

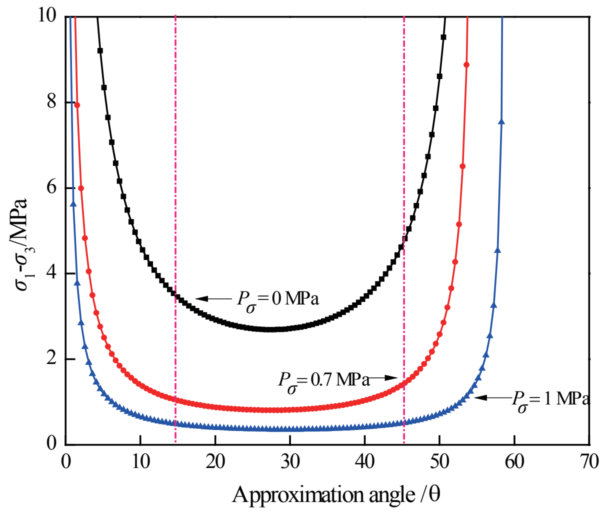
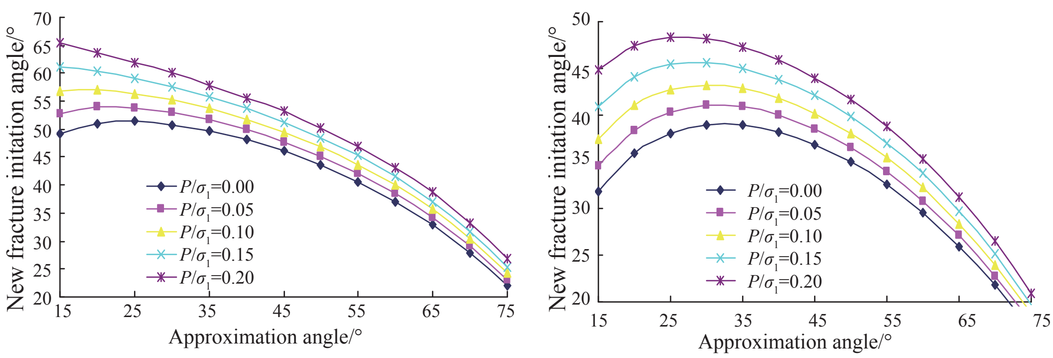


Figure 3
The Critical Level of Horizontal Stress Difference When Natural Fracture Occurs Shear Slip

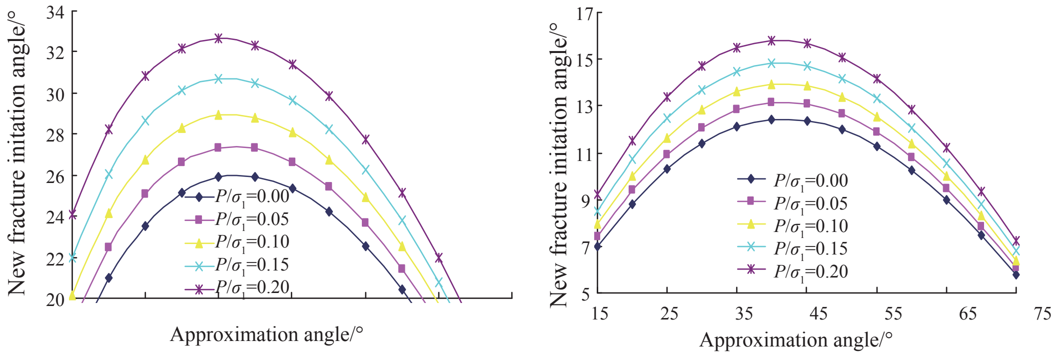
1.2.2 The Influence Factors of New Crack Initiation Angle Are Analyzed

The impact of different horizontal stress difference and pressure on new crack are calculated by (2-9), the results are shown in Figure 4.

Assuming that the horizontal crustal stress is $\frac{\sigma_3}{\sigma_1}$=0.2, $\frac{\sigma_3}{\sigma_1}$=0.4, $\frac{\sigma_3}{\sigma_1}$=0.6 and $\frac{\sigma_3}{\sigma_1}$=0.8, respectively; the pressure P is $\frac{P}{\sigma_1}$=0, $\frac{P}{\sigma_1}$=0.05, $\frac{P}{\sigma_1}$=0.10, $\frac{P}{\sigma_1}$=0.15 and $\frac{P}{\sigma_1}$=0.20, respectively.



(a) σ/3/σ/$_1$=0.2 (b) σ/3/σ/$_1$=0.4



(c) $\sigma/3/\sigma/_1$=0.6 (d) $\sigma/3/\sigma/_1$=0.8

Figure 4
New Crack Angle Under the Action of Stress Difference and Pressure

It was can be seen from the Figure 4 that the new crack Angle increases constantly with the increase of the pressure under the different horizontal stress ratio; the new crack Angle increases at first then decreases with the increase of approaching Angle, improving the pressure can change the direction of new crack significantly under the condition of lower approaching Angle.

By contrast four kinds of stress ratio (*a*, *b*, *c*, *d*), it can be found that the greater the horizontal stress difference is, the bigger the new crack initiation angle is, the new crack can be transferred to the maximum horizontal in-situ stress direction faster; while the smaller the horizontal stress difference is, the more natural fracture can be communicated, it can be explained that the network fracture is formed easier when fracturing at a low horizontal stress difference reservoir; In the case of different stress ratios and pressures, the maximum initiation angle was existed in the approaching angle which range from 20°-45°.

2. THE MODEL EXTENSIVE APPLICATION

The mathematical model which was established in this paper is adopted as the interference criterion between hydraulic fracture and natural fracture, the existing hydraulic fracture of three dimensional extension model was developed, the impact of different natural fracture dip and natural fracture intensity on network morphology were analyzed, due to the crack width and the pressure are positive correlation, so the change of the pressure is mainly analyzed. The basic parameters are: formationmodulus is 1.26×10^4 Mpa; poisson ratio is 0.13; reservoir thickness is 20 m; operational discharge capacity is 3.2 m^3/min; construction time is 40 min; consistency coefficient is 4.9 Pa·s^n; flow stance index is 0.8; overall fluid loss coefficient is 0.001 m/$min^{0.5}$; initial filtrate loss is 0.0005 m^3/m^2; tensile strength is 4.01 Mpa; the maximum horizontal in-situ stress is 42 Mpa; the minimum horizontal stress is 39 Mpa; cohesion is 0; friction coefficient is 0.6.

2.1 Effects of Natural Fracture Dip

Assuming that the distance between the first level of natural fractures and the shooting points is a constant value, the relationship between the pressure and time was discussed when the approaching Angle (α) is 30°, 15°, 45°, 60°, 75° and 90°, the results are shown in Figure 5.

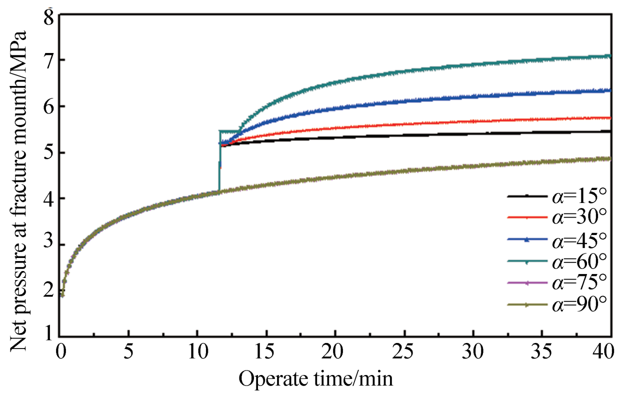


Figure 5
Relationship of Static Pressure at Fracture Opening and Time

It was can be seen from Figure 5 that the hydraulic fracture met with natural fracture after 11.5 min under the condition of the distance between natural fracture and shooting point is 50 m, and the hydraulic fracture went through the natural fractures directly when the approaching angle is 75° and 90°, would extend along natural fractures in the rest of the case. It was verified that the high approaching angle is liable to hydraulic fracture go through directly. When hydraulic fracture deflected at intersection, the pressure rose sharply, "high pressure" phenomenon was appeared briefly, and the pressure increases with the increase of approaching Angle, this is because the bigger the approaching Angle is, the greater the closing pressure which need to overcome in the process of crack propagation is.

2.2 The Effects of Natural Fracture Intensity

Natural fracture intensity for hydraulic fracturing to form network has the vital role, it can be represented by the distance between first level natural fracture and shooting point, when the approaching angle is a constant, the curve which the pressure changes with the natural fracture position is discussed, as is shown in Figure 6.

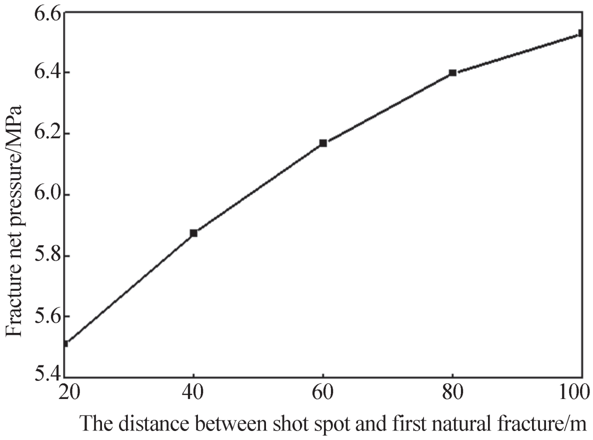


Figure 6
Relationship of Static Pressure At Fracture Opening and Location of Natural Fracture

It was can be seen from Figure 6 that the pressure which was needed by the new crack initiation increased with the increase of distance between natural fracture and shooting points, the new crack need net seam increases, this is because under the condition of same approaching Angle, the same pressure was needed by natural fracture occur shear slip, but the friction increases with the increase of distance, it can be explained that in order to get a complex fracture network in shale reservoir need to improve the pressure to activate distance of natural fracture, constantly.

CONCLUSION

Based on the linear elastic fracture mechanics theory, the formation mechanism of shale reservoir complex fracture network system are discussed in this paper, a double-slit interference model and a new crack initiation angle calculation model is established. Calculation results show that the lower approximation Angle and high pressure in the fracture is the necessary conditions of forming fracture network; under the condition of lower stress difference and high internal pressure, the new crack can connect more natural fracture.

Calculation results show that in order to get a complex fracture network in shale reservoir need to improve the pressure to activate and connect higher approaching Angle and distance of natural fracture, constantly

The existing hydraulic fracture of three dimensional extension model was developed, the impact of different natural fracture dip and natural fracture intensity on network morphology were analyzed

The research results have important reference value in understanding the formation mechanism of complex fracture network in shale reservoir, can also be used for shale fracturing design and fracturing interval optimization.

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