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Simulation Research and Application of Complex Fracture Network for SRV

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Abstract. Stimulated Reservoir Volume (SRV) is one of new emerging hydraulic fracturing techniques to develop shale gas, tight sandstone and other unconventional reservoirs. The favorable geological conditions and reasonable fracturing design are critical factors to form complex fracture network that is different from conventional bi-wing fracture. In the reservoir, conductivity and drainage space can be enhanced by the fracture network. At present, numerical simulation of complex fractures is still based on the pseudo-3D model and depend on huge amount of calculation to obtain the fracture network. Therefore, this method has distinct differences in actual propagation and need to be computed intensively. Applying the theory of mechanics of materials and fracture mechanics, the equations of expansion and propagation for natural fracture are derived and the equation of stress shadow is adopted to consider the additional normal stress induced by adjacent fractures. Based on the propagation pressure, the length of branching fracture can be obtained by establishing a novel fracture network model. The model can be solved explicitly through the net pressure. This method can reduce the iterations effectively when many natural fracture must be accounted for the realization of numerical calculation. In order to verify the accuracy of the results, the parameters applied in the treatment are adopted as input for simulation, and the data of microseismic mapping are also used for matching the fracture network.

Introduction

Hydraulic fracturing has become one of the most important technologies in the development tight oil resources. During the process of reservoir stimulation, how to create more fractures in tight sandstone reservoir becomes the key issue. However, some naturally fractured sand formations have geomechanical properties that allow hydraulically induced discrete fractures to initiate, propagate and lead to a complex fracture network. Many researchers have conducted a series of experiments and numerical simulations to investigate the mechanism of fracture propagation. Also, some key factors which affect the complex fracture network such as natural fracture, horizontal in situ stress difference, fracturing fluid viscosity, and injection rate [1,2,3,4] of fracturing fluid have been investigated.

Blanton [5,6]discussed the relationship between induced fracture and natural fracture which displayed that hydraulic fractures cross the pre-existing fractures only under high differential stress conditions and high approach angle. In addition, the stress ratio of [7, 8]maximum principal horizontal stress to minimum principal horizontal stress below 1.5 demonstrated proportionally increasing branching and fracture multiplicity with proportionally decreasing stress orientation. In other words, the hydraulic fractures are more easily to extend along the natural fracture under the low horizontal stress difference [9, 10]. Chen mian and Zhou jian [11,12] used true triaxial hydraulic fracturing test to study the effect of natural fractures on hydraulic fracture propagation, such as stress difference, approach angle. The experimental results [13,14,15]showed that horizontal stress difference and approach angle are the main factors influencing the shear failure.

Numerical simulation is another effective way to understand the mechanism of fracture propagation, many researchers have studied the fracture propagating mechanism by using 2D or 3D numerical models [1,14,16]. In multistage fracturing technology, the stress concentration have an impact on the fracture initiation and propagation of the subsequent stage under closer cluster space. Based on the displacement-discontinuity method, a 2D model [17] was established to study the stress distribution around transverse fractures and the geometries of those fractures. This paper based on the fracture mechanics, and combined with conventional hydraulic fracture theory, takes the fracture net pressure as the judgement of fracture propagation. Namely the length of branch fracture depends on the fracture net pressure. The new unconventional fracture model was established based on the idea, which not only fully considered the influence of nature fracture expansion and initiation on fracture network, but avoid the conventional fracture simulations which needs to assume the fracture length firstly, then using Runge-Kutta method and volume balance method to calculate the fracture parameters. Finally the calculation verified by the micro-seismic test data.

Fracture Initiation and Propagation Analysis of Complex Fracture Network

The criterion of nature fracture initiation is based on the mechanics theory of materials developed by Warpinski and Teufel [10]. Using the fracture mechanics to analysis the objects which contains fracture is more convenience.

Stress Intensity Factor

The propagation of nature fracture is mainly controlled by fracture net pressure and the normal stress which acts on the fracture surface. In the process of stress intensity factor calculation, according to the superposition principle of fracture mechanics, the stress intensity factor can be superimposed.

Assuming there is a couple of centralized force acts on the upper and lower surface which is away from the fracture center. And the stress intensity factor (K_{IA}, K_{IB}) under the situation can be calculated as follows.

$$K_{\mathrm{I\,A}} = \frac{P}{\sqrt{\pi a}}\sqrt{\frac{a+b}{a-b}} \tag{1}$$

$$K_{\mathrm{I\,B}} = \frac{P}{\sqrt{\pi a}}\sqrt{\frac{a-b}{a+b}} \tag{2}$$

Where, P is the centralized force acted on the fracture surface; a is the fracture half length; $K_{\mathrm{I\,A}}$ and $K_{\mathrm{I\,B}}$ are the stress intensity factors of fracture ends; b is the intersection point of nature fractures. And the stress intensity factors beside the centralized force acting point as follows.

$$K_{\mathrm{I\,A}} = \frac{P_1}{\sqrt{\pi a}}\sqrt{\frac{a+(b+x)}{a-(b+x)}} + \frac{P_2}{\sqrt{\pi a}}\sqrt{\frac{a-(b-x)}{a+(b-x)}} \tag{3}$$

$$K_{\mathrm{I\,B}} = \frac{P_2}{\sqrt{\pi a}}\sqrt{\frac{a+(b+x)}{a-(b+x)}} + \frac{P_1}{\sqrt{\pi a}}\sqrt{\frac{a-(b-x)}{a+(b-x)}} \tag{4}$$

In the hydraulic fracture process, the net pressure of fracture acts on the fracture surface continuously, but in the calculation it is discrete, and it can not fully describe the concentrated force changes in a certain period of fracture length in the stress intensity factor expression. Thus, the stress intensity factors can be calculated under concentrated force at different nodes, then superimposed stress intensity factor as the stress intensity factor under flow pressure. The expression as follows.

$$K_{\mathrm{I\,A}}^{'} = \sum_{1}^{n} K_{\mathrm{I\,A}}(P, x) \tag{5}$$

$$K_{\mathrm{I\,B}}^{'} = \sum_{1}^{n} K_{\mathrm{I\,B}}\left(P, x\right) \tag{6}$$

$$\sum_{1}^{n} K_{\mathrm{I\,A}}\left(P_0, x\right) \le K_{\mathrm{I\,C}} \quad , \quad \sum_{1}^{n} K_{\mathrm{I\,B}}\left(P_0, x\right) \le K_{\mathrm{I\,C}} \tag{7}$$

Where, K_{IC} is the toughness of rock, P_0 is the initial pressure at point b.

Judgement of Fracture Initiation and Propagation

When calculating the fracture propagation pressure and judging the generation of type I fracture, the K criterion is necessary to solve the problem.

$$K_{\mathrm{I\,A}}^{'} = K_{\mathrm{I\,C}} \tag{8}$$

$$K_{\mathrm{I\,B}}^{'} = K_{\mathrm{I\,C}} \tag{9}$$

Eq. 8 and Eq. 9 are based on fracture mechanics theory to calculate the net pressure which can determine the extension length, and the judgment criterion for fracture initiation is based on the mechanics theory of materials. By introducing the fracture initiation theory of Warpinski and Teufel, the nature fracture initiation formula under triaxial stress condition can be deduced.

$$p_f{}' = \sigma_n = \sigma_1 \cos^2 \alpha + \sigma_2 \cos^2 \beta + \sigma_3 \cos^2 \gamma \tag{10}$$

Appendant Stress Field

The appendant stress field will be formed when the stress field of hydraulic fracture affected by adjacent fracture. According to the analytical formula [14,15], the equation as follows.

$$\sigma_n^i = \sum_{j-1}^{N} G^{ij} C_{ns}^{ij} D_s^j + \sum_{j-1}^{N} G^{ij} C_{nn}^{ij} D_n^j \tag{11}$$

Mathematical Model

The mathematical model of complex fracture network is based on Palmer model [16]. According to the fracture mechanics, the mathematical model of complex fracture network was established, and the main formulas and equations as follows.

(1) The judgement of fracture initiation and extension, appendant stress field calculation as Eq. 6~9.

(2) Fracture width equation.

Assuming the layer is thick enough, namely $h_i(x,t) < H_p$, and the fracture net pressure is $P(z) = P_f\left(x,t\right) - \sigma_n^{'}$, and the fracture width of arbitrary z point of cross section as follows.

$$w_i(x,z,t) = \frac{4\left(1-\upsilon^2\right)}{E}\left(P_f - \sigma_n^{'}\right)\sqrt{l^2 - z^2} \tag{12}$$

(3) Pressure drop equation

According to the panel pressure drop equation [17], and introduce the pipe shape factor into it, the fracture internal pressure drop equation as follows.

$$\frac{\partial P_i(x,t)}{\partial x} = -2^{n+1}\left[\frac{(2n+1)q_i(x,t)}{n\phi_i(n)h_i(x,t)}\right]^n \frac{K}{\left[w_i(x,0,t)\right]^{2n+1}} \tag{13}$$

(4) Fracture height equation

Adopting the stress intensity integral formula to get the fracture height of the quasi-three dimensional implicit expression.

$$K_I = \frac{1}{\sqrt{\pi h_i(x,t)}} \int_{-h_i(x,t)/2}^{h_i(x,t)/2} P_i(z) \frac{\sqrt{h_i(x,t)/2+z}}{\sqrt{h_i(x,t)/2-z}} dz \tag{14}$$

(5) Continuity equation

$$-\frac{\partial q_i(x,t)}{\partial x} = \frac{2h_i(x,t)\cdot C_t(x,t)}{\sqrt{t-\tau(x)}} + \frac{\partial A_i(x,t)}{\partial t} \tag{15}$$

The simulation of every induced fracture is the basic of complex fracture network. Based on the mathematical model of complex fracture network, and taking the main fracture net pressure or initial pressure of intersection point as the initial value, according to Eq. 14 to determine the fracture height, then according to the Eq. 13 to decide the fracture width and the pressure distribution according to the Eq. 13. After determining the fracture length, the pressure distribution will be clear according to Eq. 13, and it will be the initial value for the next step.

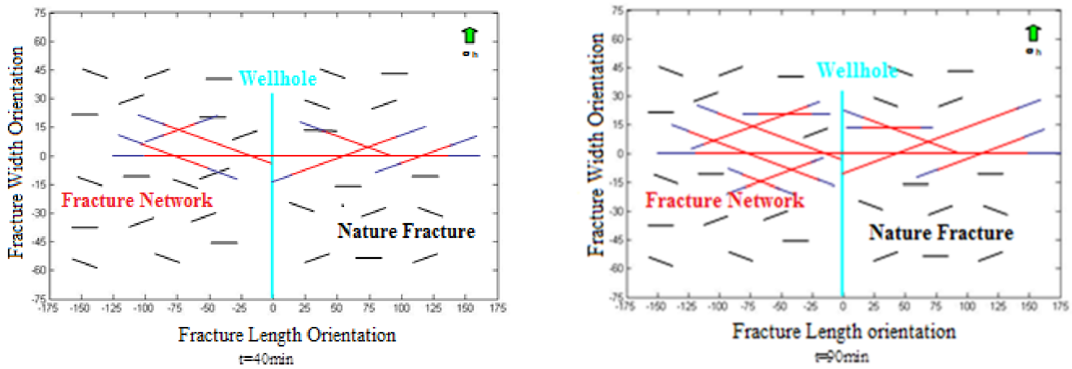
Result and Analysis

Taking an oilfield as an example. The geology data and operation data for SRV as follows.

Table 1. The basic parameters of fracturing for SRV

Parameter	Value
The maximum horizontal stress	87.5MPa
The minimum horizontal stress	85.3MPa
Young modulus	23.37GPa
Poisson Rate	0.25
Fracturing fluid initial viscosity	155mPa•s
Fracturing fluid density	1.02g/cm^3
Flow regime index	0.433
Consistency coefficient	4.74Pa•s^n
Total fracturing fluid leak-off coefficient	0.00119m•min$^{-0.5}$
Fracture Toughness	1.21MPa•m$^{0.5}$
Flow rate	3.2m^3
Bottom pressure	90MPa
Operating time	90min

From geological model and sonic logging data, it can be concluded that the stress difference between the maximum horizontal stress and the minimum horizontal stress is small, and the nature fracture orientation is not parallel to the maximum horizontal stress. In formation, the nature fracture distributed with an angle between the minimum horizontal stress orientation (70°, 90°or 110°).



(a) (b)

Figure 1. Planar graph of fracture network when simulation time at 40min (a) and 90min (b)

Based on the input data(Table 1), the physical process that the hydraulic fracture intersect with nature fracture has been stimulated, and the complex fracture network has been obtained. In Fig. 1(a) and (b), the red line means the fracture has been opened completely, the blue line means the extension fracture because of the fracture internal pressure is less than initiation pressure but over extension pressure which demonstrated the brittle failure. With the nature fracture extension, the fracture internal pressure will decrease, so the extended length (blue line) will decrease continuity. It should be stressed that with the closure stress decrease and shear effect, it has conductivity though the nature fracture has not been opened completely.

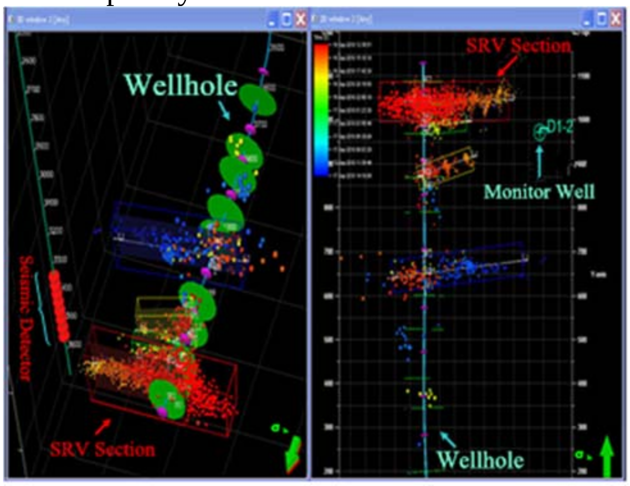


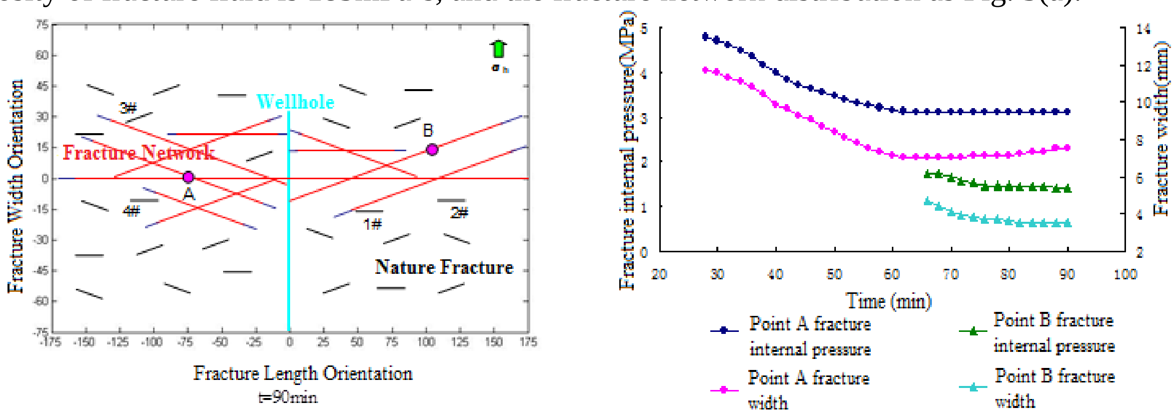
Figure 2. Microseismic mapping of fracturing for SRV

Because of the SIF and leak-off effect, the microseismic data is not symmetrical and regular, and it is closely related to the fracture network geometrical morphology and fracture complex degree. Compared microseismic data (Fig. 2) with simulation result, on the one side of horizontal well, the nature fracture density is bigger than that on the other side, and the probability of nature fracture intersection with main fracture or branch fracture is bigger, which means the more complex of the fracture network is. From the stimulation, the length and width of fracture network matches well with microseismic data.

Discussion

Influence of Geological and Operating Parameters on the Fracture Network Parameters and Complex

In order to analysis the influence of geological and operating parameters on the fracture network parameters and complex, assuming the bottom pressure is 92.5MPa, the flow rate is $4.6m^3$,the viscosity of fracture fluid is 185mPa•s, and the fracture network distribution as Fig. 3(a).



(a) (b)

Figure 3. Planar graph of fracture network with favorable parameters as input (a) and the trend line of net pressure and width at different point (b)

From Fig. 3(a) it can be concluded that increasing the injection pressure, flow rate, and optimize the fracture fluid can make the stimulated volume bigger at the same time. As demonstrated in Fig. 3(a), the probability of extension fracture (blue line) decreased while the opened fracture (red line) increased sharply. With the decrease of horizontal stress difference, the angle of nature fracture is distributed in random, when the nature fracture perpendicular to the maximum horizontal stress, the initiation pressure comes to the biggest, it is difficult to make it opened.

Influence of Postulated Conditions

In this research, the flow rate after the nature fracture intersected with hydraulic fracture is distributed by the number of branch fracture. As seen in Fig. 3(a), when the branch fracture density is high (as point A), in the initial stage, the net pressure decreased sharply, and the fracture width dropped significantly. With the extension of the branch fracture, the appendant stress of point A obviously decreased, in the later stage, the net pressure change is not obvious (seen as Fig. 3(b)). With the increase of fracture height, the fracture width increased slightly. As for point B, because of the branch fracture density is relatively low, the effect of appendant stress is very weak. From the whole process, the extension of the branch fracture is still affected by appendant stress (seen as Fig. 3(b)).

Conclusion

(1) The judgement of fracture initiation and propagation is an important foundation to determine the fracture network geometry and complex. Taking the fracture internal pressure as the judgement can not only sufficiently explain the fracture initiation and propagation progress, but also can provide a convenient method for the model to get the numerical solution.

(2) The stimulation of fracture network is obviously affected by in-situ stress, rock properties, nature fracture size, nature fracture distribution, operating parameters. The accurate geological model and operating design is the key to complicated fracture network.

(3) Microseismic monitoring technology is one of the important means to verify the geological model. Taking the microseismic source as the benchmark to improve the geological model which can get more accord with the actual fracture network

(4) In the stimulation, it is very difficult to stimulate the nature fracture which distributed with arbitrary angle intersect with hydraulic fracture, and the key point is the flow rate distribution after intersection. So it is necessary to study further in numerical solution, stimulation.

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