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Research article

Simulation of complex fracture networks influenced by natural fractures in shale gas reservoir

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Abstract

When hydraulic fractures intersect with natural fractures, the geometry and complexity of a fracture network are determined by the initiation and propagation pattern which is affected by a number of factors. Based on the fracture mechanics, the criterion for initiation and propagation of a fracture was introduced to analyze the tendency of a propagating angle and factors affecting propagating pressure. On this basis, a mathematic model with a complex fracture network was established to investigate how the fracture network form changes with different parameters, including rock mechanics, in-situ stress distribution, fracture properties, and frac treatment parameters. The solving process of this model was accelerated by classifying the calculation nodes on the extending direction of the fracture by equal pressure gradients, and solving the geometrical parameters prior to the iteration fitting flow distribution. With the initiation and propagation criterion as the bases for the propagation of branch fractures, this method decreased the iteration times through eliminating the fitting of the fracture length in conventional 3D fracture simulation. The simulation results indicated that the formation with abundant natural fractures and smaller in-situ stress difference is sufficient conditions for fracture network development. If the pressure in the hydraulic fractures can be kept at a high level by temporary sealing or diversion, the branch fractures will propagate further with minor curvature radius, thus enlarging the reservoir stimulation area. The simulated shape of fracture network can be well matched with the field microseismic mapping in data point range and distribution density, validating the accuracy of this model.

Keywords: Shale gas; Hydraulic fracturing; Initiation and propagation criterion; Propagating angle; Propagating pressure; Fracture network; Complex fracture model

The conventional hydraulic fracturing simulation usually assumes that there are no natural fractures in the homogeneous formation, and on two sides of the borehole produce bi-wing, symmetric and planar fractures perpendicular to the minimum principal stress [1]. However, both the direct fracturing test in well [2] and indirect micro-seismic monitoring [3] show asymmetric and irregular fracture networks will form in shale gas reservoirs with natural fractures.

The initiation and propagation of natural fractures are the basis for the formation of fracture network. By experimental and theoretical analysis, many researchers have studied the physical phenomenon after the intersection of artificial and natural fractures and established the criterion for fracture propagation [4,5]; Warpinski [6] investigated the shear slip failure triggered by shearing stress on the fracture surface by the line friction theory, and analyzed the tensile failure triggered by normal stress on the fracture surface with Mohr–Coulomb Criterion. Beugelsdijk et al. [7] analyzed the effect of horizontal stress difference, displacement and viscosity on branch fracture propagation by experiment. The

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research shows that the complexity of fracture network intersected with natural fractures is not only related to the crustal stress but also mechanics, natural fracture and fracturing parameters as well as physical property of working fluid [8–10].

After the artificial fracture intersects the natural fracture, the initiation and propagation mechanism of branch fractures greatly impact the geometry and complexity of the fracture network. Based on the theory of fracture mechanics, the author introduced the criterion of initiation and propagation of fractures; on this basis, considering the influence of additional stress field, the complex fracture network model was constructed for complex fracture network created during shale gas reservoir fracturing, in the solution process the calculation nodes are divided by equal pressure gradient on the propagation direction of the fracture, and the fracture network is figured out with the node pressure as key variable; moreover, the initiation and propagation criterion is taken as the basis to identify the propagation of branch fractures to avoid the complicated fitting of the fracture length in the conventional 3D fracture simulation. Compared with the line network model [11], this model fully considers the effect of random fractures on the whole fracture network structure, and the shape of fracture network on two sides of borehole is asymmetric and the branch fractures inside are not evenly spaced, which fits the micro-seismic monitoring results better. Compared with the unconventional fracture model [12], the established initiation and propagation criterion takes into account the crack tip circumferential stress under the joint action of shear and normal stress, which can rationally explains the phenomenon of crack diversion during the propagation and calculates the angle change during the extension of branch fractures; and the calculation can be effectively accelerated by improving the numerical solution.

1. Conditions for fracture initiation and propagation

1.1. Stress intensity factor produced by shear stress

The type II stress intensity factor created by shear stress on the surface of oval natural fracture under the crustal stress is:

$$K_{\mathrm{II}} = \frac{4\sqrt{\tau b \kappa^2}}{\Theta}\left(\frac{1}{C}\sin\omega\sin\theta\frac{\kappa'}{B}\right) \quad (1)$$

$$\Theta = \left(\sin^2\theta + \frac{b^2}{a^2}\cos^2\theta\right)^{1/4},\ B = (k^2-\upsilon)E(k) + \upsilon k'^2 K(k),\ C = (k^2+\upsilon k')E(k) - \upsilon k'^2 K(k),\ k = 1-\frac{b^2}{a^2},\ k' = \frac{b}{a}$$

where $K(k)$ and $E(k)$ are the complete integral of the first and second kind of ellipse, respectively; τ is shear stress, MPa; υ is Poisson's ratio; ω is the intersection angle between the shear stress direction and elliptic long axis; θ is the intersection angle between any point at the elliptic margin and long axis; a and b is the length of fracture half long and short axis, respectively, m.

1.2. Stress intensity factor produced by normal stress

During the propagation of hydraulic fracture, the continuously extending fracture length and the intra-fracture pressure re-distribution will lead to the dynamic variation of crack tip stress intensity factor triggered by normal stress. The nodes are divided by the equal pressure gradient along the fracture extending direction at the initial cracking position, and then the superimposition principle is employed to calculate the value of crack tip stress intensity factor under different node pressures. And the division of pressure nodes is shown in Fig. 1

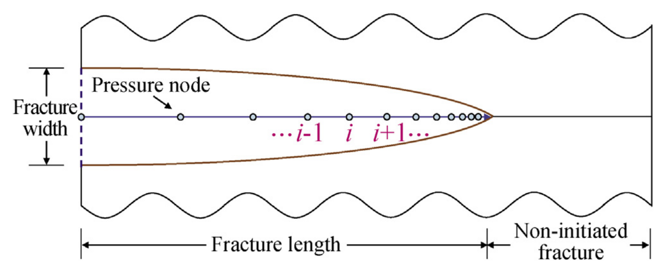

Figure 1. Division of fracture pressure nodes.

The stress intensity factor generated by different node pressure [13]:
where l(i) is the space from the pressure node No. i to the initial position; l is artificial fracture length; $P_{\mathrm{net}}(i)$ is the net pressure at the node No. i.

On this basis, the type I stress intensity factor under the normal stress can be expressed as:

$$K_{\mathrm{I}(i)} = \frac{p_{\mathrm{net}(i)}}{\sqrt{\pi l}}F \quad (2)$$

$$F = \sqrt{\frac{1-\eta}{2}}\left[\frac{2}{1-\eta} + 0.978\,8 + 1.11(1-\eta) - 0.319\,4(1-\eta)^2 - 0.101\,7(1-\eta)^3\right],\ \eta = \frac{l_{(i)}}{l}$$

$$K_{\mathrm{I}} = \sum_{i=1}^{n} K_{\mathrm{I}(i)}\left[p_{\mathrm{net}(i)},\ l_{(i)},\ l\right] \quad (3)$$

where n is the number of total pressure nodes divided.

1.3. Additional pressure field

When extending at the same time, multiple branch fractures will be influenced by the normal and shear stress of the