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Induced stress interaction during multi-stage hydraulic fracturing from horizontal wells using boundary element method

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Abstract

Multistage hydraulic fracturing is commonly applied to enhance gas productivity in unconventional reservoirs. Since the multiple fractures are created and propagated simultaneously or in a sequential manner from perforation clusters, the induced stress interference is a predominant reservoir geomechanical consideration in multi-stage hydraulic fracturing design. This paper presents a numerical model for multiple fracture propagation and induced stress analysis in multi-stage horizontal wells. The reservoir rock is assumed linear elastic, homogenous and isotropic. The influences of original stress condition, perforation numbers, wellbore inclination angles and some critical parameters on the feasibility of complex fracture network generation are investigated. The results demonstrate that the stress interference of the simultaneous initiation of fractures in simultaneous perforation manner is greater than conventional sequential perforation manner in one stage, which is beneficial for complex fracture network complexity. Under sequential fracturing manner, the induced stress increases with the increased length of the pressurized fracture. Moreover, the perforation orientations and original horizontal stress difference controls the stress interference simultaneously and then affect complex fracture network generation. In particular, if the horizontal stress difference is great, it's hard to create complex fracture network under current hydraulic fracturing stimulation technology.

Keywords: stress interference; boundary element method; complex fracture network; horizontal well;

1. Introduction

In recent years, unconventional reservoirs like shale gas and tight gas are expected to account for vast gas supply all over the world. Permeability for unconventional reservoir formations generally range from 1md down to 1μd or less, thus the novel stimulation technology is necessary to substantially improve the quality of unconventional reservoirs and required for increased final gas recovery. The horizontal well with multiple transverse fractures has proven to be an effective strategy for commercial shale gas reservoir exploitation. The aim of multi-stage hydraulic fracturing is to create complex fracture network or stimulated reservoir volume (SRV), which can be identified by microseismic mapping (**Warpinski et al. 2009; Soliman and Augustine, 2010**). However, the shape and growth extend of the SRV residing in the stimulated formation depend on many uncertainties such as the rate of fluid injection, mechanical properties (elastic Young's modulus and Poisson's ratio), anisotropic stress filed for each layers, the viscosity of injected fluid, the spacing of fractures, formation mechanical properties et al. Until now, no one can totally guarantee the success of hydraulic fracturing treatment in unconventional reservoirs without appropriate fracture modeling scenario. However, creating far-filed fracture complexity using stress interference between fractures to create regions of low horizontal-stress anisotropy has been demonstrated to improve long-term production performance. Therefore, under given geological stress conditions, how to create low horizontal-stress anisotropy is a practical challenge for hydraulic fracturing engineers with respect to engineering principles and economic justifications.

Previous numerous literatures once studied the analytical and numerical multiple fracture models under different assumptions and geological features. Sneddon introduced an analytical solution to analyze the stress state around an elliptical fracture. (**Sneddon, 1946**). Cheng used BEM approach to investigate the interaction mechanism between parallel fractures (**Cheng, 2009**). Soliman proposed an alternating-sequence fracturing method to enhance connectivity to fracture networks by minimizing stress anisotropy using stress interference (**East et al., 2011**). Rafiee et al. once investigated the spacing between fractures on stress interference using boundary element method (BEM) (**Rafiee et al., 2012**). **Roussel and Sharma (2011)** performed extensive analysis using finite element method to understand multiple fracture propagation and pressure change in different shales. **Wu and Olson (2015)** also establish a three dimensional multiple fracture model based on displacement discontinuity and finite element. The problem of fluid flow and rock deformation coupling was solved iteratively using Newton-Raphson and Picard iterative method. Similar to previous studies, they demonstrated closer spacing between fractures can result in greater stress interference while bring with high screen-out risks.

From the above discussion, the majority of studies tend to explain the complex stress interference in one stage. To better understanding the potential of complex fracture network generation and optimize the perforation treatments along horizontal wellbores, a two-dimensional (2D) multi-stage hydraulic fracturing model is developed using finite element method. This model is able to simulate multiple transverse fracture propagation from horizontal wells. In addition, we investigate the effect of fracture spacing on the change of stress anisotropy and fracture from different scales, stage to stage and perforation to perforation. Furthermore, the likelihood of complex fracture network can be evaluated.

2. Experiments

2. Theory

2.1 Stress interference between fractures

To generate complex fractures in the reservoir, certain in-situ stress requirements have to be met. The effect of the stress on the fracture geometry is mainly determined by the magnitude of two principle horizontal stresses difference, which can be reflected in the horizontal stress differential factor, K_h, which can be defined as:

$$K_h = \frac{\sigma_H - \sigma_h}{\sigma_h} \tag{1}$$

where σ_H and σ_h respectively stand for the maximum and minimum horizontal stress (MPa).

When the difference between the horizontal principal stresses and the horizontal stress differential factor are relatively low, the hydraulic fracture cracks initially towards multiple directions and forms multiple (branch) fractures during propagation, of which the propagation path is tortuous and the geometry complex. With the increase of the horizontal stress difference and differential factor, the control of the stress grows and the multi-fracture phenomenon of hydraulic fractures gradually weakens. When the stress differential factor reaches a specified value, the development of hydraulic fractures will be mainly determined by the stress and the fracture will propagate along the direction of the minimum horizontal principal stress with a relatively simple fracture geometry. According to the numerical simulation of the SINOPEC Research Institute of Petroleum Engineering, in shale reservoirs, sufficient fracture networks can be produced with a horizontal stress differential factor of 0~0.3; high net pressures are required in hydraulic fracturing for desired fracture networks with a horizontal stress differential factor of 0.3~0.5 and the net fracture propagation pressure is larger than the horizontal stress difference; with a horizontal stress differential factor larger than 0.5, fracture networks cannot form in hydraulic fracturing.Under the stress interference, the in-situ horizontal principal stresses change, and hence Eq.(1) changes into:

$$K_h = \frac{\left(\sigma_H + \sigma_H{'}\right) - \left(\sigma_h + \sigma_h{'}\right)}{\sigma_h + \sigma_h{'}} = \frac{\Delta\sigma - \Delta\sigma'}{\sigma_h + \sigma_h{'}} \tag{2}$$

where σ_H' and σ_h' respectively stand for the stress perturbation induced by fracture formation in the direction of the maximum and minimum horizontal principal stress; $\Delta\sigma$ and $\Delta\sigma'$ are respectively the differences of in-situ horizontal principal stress and stress perturbation.

If the difference of in-situ horizontal stresses is less than that of the stress perturbation, the directions of the maximum and minimum horizontal principal stress will reverse and $K_h < 0$. In this case, the fracture in the stress reverse region turn to the new direction of the maximum horizontal principal stress. For instance, the horizontal wellbore is towards the direction of the minimum horizontal principal stress, which is often the case. Under the in-situ stress condition, transverse fractures perpendicular to the wellbore occur. However, in the region with the stress perturbation induced by fracture formation, fractures may turn round towards the direction parallel to the wellbore during propagation. The deflection of the main fracture will help connecting the natural fractures and increase the fracture complexity.

2 Fracture propagation model

2.1 Failure Criterion

In hydraulic fracturing, both tensile failure and shear failure happen under complex stress conditions. Only the maximum tensile stress equals to the stress intensity factor at the fracture tip, the fracture starts to initiate and propagate. According to stress superposition theory, the stress filed of fracture tip can be illustrated as:

$$\begin{aligned}
\sigma_r &= \frac{1}{2\sqrt{2\pi r}}\left[K_I\left(3-\cos\theta\right)\cos\frac{\theta}{2}+K_{II}\left(3\cos\theta-1\right)\sin\frac{\theta}{2}\right]\\
\sigma_\theta &= \frac{1}{2\sqrt{2\pi r}}\cos\frac{\theta}{2}[K_I\cos^2\frac{\theta}{2}-K_{II}\sin\theta]\\
\tau_{r\theta} &= \frac{1}{2\sqrt{2\pi r}}\cos\frac{\theta}{2}[K_I\sin\theta+K_{II}\left(3\cos\theta-1\right)]
\end{aligned}\tag{3}$$

The failure criterion can be shown as:

$$\cos\frac{\theta_O}{2}=\left[K_I\cos^2\frac{\theta_O}{2}-\frac{3}{2}K_{II}\sin\theta_O\right]=K_{IC}\tag{4}$$

2.2 Induced stress

Induced stress can be generated when fracture start to initiate and propagate in rock. Senddon once defined analytical solution to analyze the induced stress distribution by one elliptical fracture.

$$1/2(\sigma_x+\sigma_y)=-p[\frac{L}{\sqrt{L_1L_2}}\cos(\theta-1/2(\theta_1+\theta_2))-1]\tag{5}$$

$$1/2(\sigma_y-\sigma_x)=p[\frac{L\sin\theta}{h/2}(\frac{h^2/4}{L_1L_2})^{3/2}\times\sin(\frac{3}{2}(\theta_1+\theta_2))]\tag{6}$$

$$\tau_{xy}=-p[\frac{L\sin\theta}{h/2}(\frac{h^2/4}{L_1L_2})^{3/2}\times\cos(\frac{3}{2}(\theta_1+\theta_2))]\tag{7}$$

$$L=\sqrt{x^2+y^2};\theta=\tan^{-1}(x/-y);L_1=\sqrt{x^2+(y+h/2)^2};$$
$$L_2=\sqrt{x^2+(y-h/2)^2};\theta_1=\tan^{-1}[x/-y-h/2];\theta_2=\tan^{-1}[x/(h/2-y)]; \quad (8)$$

Where p is the pressure in the crack (MPa); h is the length of the crack (m); σ_x and σ_y, and τ_{xy} are the induced stresses (MPa). L, L_1 and L_2 are the distances of any point A to the middle, top, and bottom of the crack, respectively (m). θ, θ_1, and θ_2 are their corresponding angles (deg).

2.3 Displacement discontinuity model

Based on BEM for displacement discontinuity problems, a fracture is discretized into a number of small linear elements. The displacement discontinuity D, is defined as the difference in displacement between two sides of the element. Dx and Dy represent as:

$$D_x=u_x(x,0_-)-u_x(x,0_+) \quad (9)$$

$$D_y=u_y(x,0_-)-u_y(x,0_+) \quad (10)$$

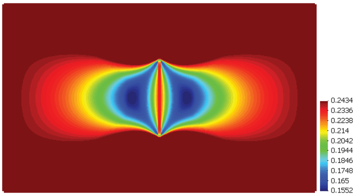
With the specified fracture boundary conditions, the displacement difference (D) of the two edges of any element may be solved by employing the principle of superposition to all elements one by one, by which the stress and displacement at any arbitrary point i, in the region can be obtained with the following equation:

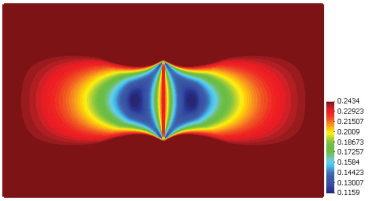
$$\sigma_s^i=\sum_{j=1}^{N}A_{ss}^{ij}D_s^j+\sum_{j=1}^{N}A_{xn}^{ij}D_n^j \quad (11)$$
$$\sigma_n^i=\sum_{j=1}^{N}A_{ns}^{ij}D_s^j+\sum_{j=1}^{N}A_{nn}^{ij}D_n^j \quad (12)$$
$$u_s^i=\sum_{j=1}^{N}B_{ss}^{ij}D_s^j+\sum_{j=1}^{N}B_{xn}^{ij}D_n^j \quad (13)$$
$$u_n^i=\sum_{j=1}^{N}B_{ns}^{ij}D_s^j+\sum_{j=1}^{N}B_{nn}^{ij}D_n^j \quad (14)$$

The equations compose a system of 2N simultaneous linear equations with 2N unknowns. They are the element displacement discontinuity components of D_s^j and D_n^j.

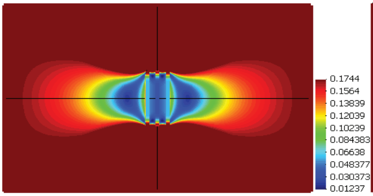
3 Numerical simulation

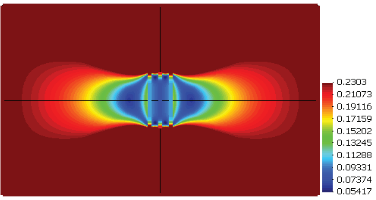
3.1 the effect of net pressure on K_h *for one perforation*





3.2 the effect of net pressure on K_h *for multiple perforations*





4. Conclusions

(1) The simultaneous multi-cluster fracturing with multi-stage and multi-cluster perforation is more favorable to utilize stress interference to create complex fractures, than single-stage fracturing with single stage perforation. For the in-situ stress condition and formation properties in the study area, complex fractures can occur in the region with the horizontal stress differential factor of 0~0.3 under stress interference. Horizontal drilling along the direction of the minimum horizontal stress is conducive to complex fracture generation.

(2) The half-length, net pressure and inclination angle of the early-generated fracture and fracture spacing have effects on the probability of formation of complex fractures.

(3) The larger the net pressure of the pressurized fracture is, the greater the stress perturbation induced by fractures is and so is the feasibility of subsequent fractures forming complex networks. The net pressure should be designed as high as possible in real practice to increase the fracture network feasibility, with the pressure limitation of surface pipelines and strings taken into consideration.

References

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