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RESEARCH PAPER

A criterion for identifying hydraulic fractures crossing natural fractures in 3D space

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Abstract: Based on the analysis of the stress fields near the hydraulic fracture tip and on the natural fracture surface, a criterion for identifying hydraulic fractures crossing natural fractures was proposed. A series of hydraulic fracturing tests were conducted to investigate the influences of natural fractures occurrence and horizontal stress contrast on hydraulic fracture propagation using large scale tri-axial fracturing system. The experiment results showed that the crossing happens in the region with high approaching angle and strike angle, large horizontal stresses and horizontal stress difference coefficient. Horizontal stress contrast has a critical value, only when it is above the critical value, may the hydraulic fracture cross the natural fracture. These experimental results agree with the predictions of this criterion well. It is predicted by this criterion that the hydraulic fracture of a test well in the Longmaxi shale formation, Sichuan Basin, can't cross the natural fracture, which agrees with the micro-seismic monitoring results.

Key words: shale; hydraulic fracturing; natural fracture; hydraulic fracture; occurrence

Introduction

Large scale hydraulic fracturing is commonly used to stimulate the reservoir in the development of unconventional oil and gas reservoirs [1–4]. The complexity of hydraulic fracture network depends on the intersection between hydraulic and natural fractures.

Experiments conducted by Norman [5] et al and Daneshy [6] et al proved that the strength of weak plane, its azimuth, and the horizontal stress difference are key factors affecting the intersection between hydraulic and natural fractures. In order to predict whether a natural fracture opens or shear slips [7], a variety of criteria have been proposed, such as Warpinski criterion [8], Renshaw criterion [9] and Zhou criterion [10-11]. These criteria were further used to judge the intersection between hydraulic and natural fractures [12–15]. However, focusing on the interaction between two vertical fracture planes, all these criteria and experiments only considers the effect of natural fracture strike angle but neglect the effect of dip angle on the intersection of hydraulic and natural fractures. Therefore, in 3D space, a new criterion to identify intersection of hydraulic fractures and natural fractures was proposed in this paper, and a series of large scale tri-axial fracturing tests were conducted to prove the validity of this new criterion. Then, this criterion was used in predicting whether the hydraulic fracture of a test well in Longmaxi shale formation, Sichuan basin, could cross the natural fracture.

1 Intersection criterion of hydraulic and natural fractures

Taking the directions of three principal stresses ($\sigma_1 > \sigma_2 > \sigma_3$,where $\sigma_V = \sigma_1, \sigma_H = \sigma_2, \sigma_h = \sigma_3$) as coordinate axes, a spatial coordinate system (1,2,3) is built (Fig.1), in which the normal vector of the natural fracture (*NF*) is

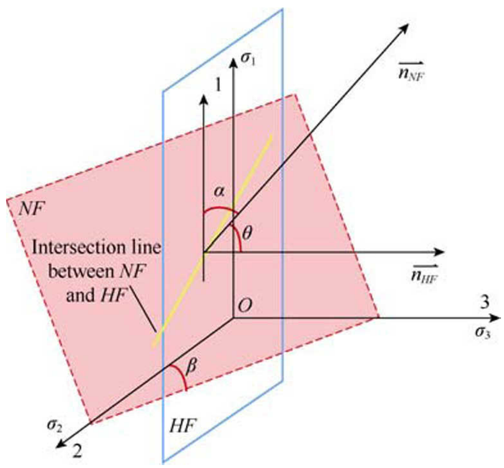

Fig. 1 Spatial schematic of a natural and hydraulic fracture

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$\overline{n_{NF}} = (l_1, l_2, l_3)$. The hydraulic fracture generally propagates perpendicularly to the minimum pricinple stress at high stress difference. Thus, its normal vector is $\overline{n_{HF}} = (0, 0, 1)$. The angle between the natural and hydraulic fracture named as approaching angle, is expressed as:

$$\theta = \arccos\left(\overline{n_{HF}} \cdot \overline{n_{NF}}\right) \quad (1)$$

If the natural fracture is a plane, the normal stress and shear stress acting on the plane by the remote in-situ stresses are given by:

$$\begin{cases} \sigma_{\text{in}} = \sigma_1 l_1^2 + \sigma_2 l_2^2 + \sigma_3 l_3^2 \\ \tau_{\text{in}} = \sqrt{\sigma_1^2 l_1^2 + \sigma_2^2 l_2^2 + \sigma_3^2 l_3^2 - \left(\sigma_1 l_1^2 + \sigma_2 l_2^2 + \sigma_3 l_3^2\right)^2} \end{cases} \quad (2)$$

The direction of the shear stress is expressed as

$$\overline{n_{\tau_{\text{in}}}} = \left(\frac{\sigma_1 - \sigma_{\text{in}}}{\tau_{\text{in}}} l_1, \frac{\sigma_2 - \sigma_{\text{in}}}{\tau_{\text{in}}} l_2, \frac{\sigma_3 - \sigma_{\text{in}}}{\tau_{\text{in}}} l_3\right) \quad (3)$$

A special plane, which is perpendicular to the natural and hydraulic fracture, satisfies plane strain (Fig. 2). The angle ϖ between σ_1 and the intersection line of hydraulic and natural fracture satisfies the relationship:

$$\varpi = \arccos\left[\left(\overline{n_{HF}} \times \overline{n_{NF}}\right) \cdot (1, 0, 0)\right] \quad (4)$$

Therefore,

$$\sigma_4 = \sigma_2 \cos^2\varpi + \sigma_1 \sin^2\varpi \quad (5)$$

The linear superposition of stress field and remote in-situ stress at hydraulic fracture tip is expressed as:

$$\begin{cases} \sigma_x = -\sigma_4 + \dfrac{K_{\text{I}}}{\sqrt{2\pi r}} \cos\dfrac{\vartheta}{2}\left(1 - \sin\dfrac{\vartheta}{2}\sin\dfrac{3\vartheta}{2}\right) \\ \sigma_y = -\sigma_3 + \dfrac{K_{\text{I}}}{\sqrt{2\pi r}} \cos\dfrac{\vartheta}{2}\left(1 + \sin\dfrac{\vartheta}{2}\sin\dfrac{3\vartheta}{2}\right) \\ \tau_{xy} = \dfrac{K_{\text{I}}}{\sqrt{2\pi r}} \sin\dfrac{\vartheta}{2}\cos\dfrac{\vartheta}{2}\cos\dfrac{3\vartheta}{2} \end{cases} \quad (6)$$

Fracture mechanics assumes that material yield at fracture process zone ($r<r_c$) within which stresses mainly depend on the micromechanical deformation mechanisms acting at the tip. The stresses within the process zone region are not above the stresses at $r=r_c$. The maximum tensile stress of model I hydraulic fracture tip occurs at $\vartheta=0°$, and is expressed as:

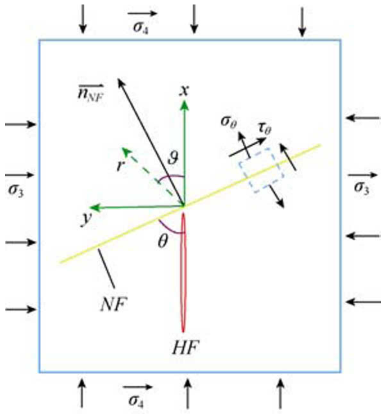

Fig. 2 Schematic of hydraulic fracture approaching natural fracture at non-orthogonal angles

$$\sigma_y\big|_{\vartheta=0} = \frac{K_{\text{I}}}{\sqrt{2\pi r_c}} - \sigma_3 \quad (7)$$

A hydraulic fracture must meet tow conditions to cross a natural fracture: (1) The maximum tensile stress at the hydraulic fracture tip is equal to the tensile strength of the rock on the opposite side of the natural fracture; (2) No shear slippage occurs in the natural fracture surface. These two conditions can be expressed as:

$$\sigma_y\big|_{\vartheta=0} = T_0 \quad (8\text{-}1)$$

$$|\tau_\theta| < \tau_0 - \mu\sigma_\theta \quad (8\text{-}2)$$

The normal and shear stress acting on the right wing ($\vartheta=-\theta$) of the natural fracture by the hydraulic fracture tip stress field can be expressed as:

$$\begin{cases} \sigma_{t,-\theta} = (\sigma_3 + T_0)\cos^3\dfrac{\theta}{2} \\ \tau_{t,-\theta} = -(\sigma_3 + T_0)\sin\dfrac{\theta}{2}\cos^2\dfrac{\theta}{2} \end{cases} \quad (9)$$

The normal and shear stress acting on the left wing ($\vartheta=\pi-\theta$) of the natural fracture by the hydraulic fracture tip stress field can be written as

$$\begin{cases} \sigma_{t,\pi-\theta} = (\sigma_3 + T_0)\sin^3\dfrac{\theta}{2} \\ \tau_{t,\pi-\theta} = (\sigma_3 + T_0)\cos\dfrac{\theta}{2}\sin^2\dfrac{\theta}{2} \end{cases} \quad (10)$$

Superposing Eqs. (9)-(10) and (2) respectively, the total normal and shear stress at the right and left wing of the natural fracture can be obtained. The hydraulic fracture crosses the natural fracture when these two groups of stresses satisfy Eq. (8).

When the direction of σ_1 is parallel with the natural fracture, this criterion is similar to the Gu [15] criterion. When the direction of σ_1 is parallel with the natural fracture and θ=90°, τ_0=0, stress state is shown in Fig. 3. The comparison (Fig. 4) between this criterion and Renshaw [9] criterion, Gu [15] criterion indicates there are some minor differences between the three curves, which is caused by the intersection condition of Eq. (8-1). The tensile stress at ϑ=90° is compared with tensile strength of rock in Renshaw criterion, which is not reasonable because this direction is 90° different from the tip propagation.

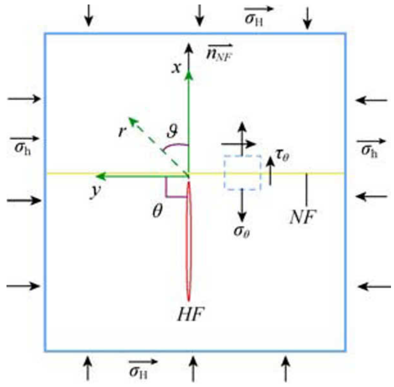

Fig. 3 Schematic of hydraulic fracture approaching natural fracture at orthogonal angle