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RESEARCH PAPER

Experimental investigation on fracture initiation and non-planar propagation of hydraulic fractures in coal seams

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Abstract: True tri-axial test system was deployed for fracturing simulation of coal outcrops to investigate the initiation and propagation of hydraulic fractures in vertical and directional wells. The influences of in-situ stress and cleats on non-planar propagation of hydraulic fractures in directional wells under different relative azimuths were analyzed. The test results show that the general propagation pattern of hydraulic fractures is jointly controlled by azimuth, cleats and in-situ stress. As the relative azimuth increases, the hydraulic fractures become more complicated in geometry and subject to increasing pumping pressure and propagation pressure. If the hydraulic fractures are initiated along a direction skewed with wellbore, the effect of cleats would alter the extension path and appear distortion of hydraulic fractures, inducing more complicated fracture geometry near the wellbore, with many fractures at the initiation point. Compared with vertical wells where I-shaped or X-shaped hydraulic fractures are formed, directional wells often have twisty propagation of dominant fractures near the wellbore and presence of multi-level fractures, which impede the further extension of hydraulic fractures in coal seams.

Key words: coal seams; directional well; hydraulic fracturing; fracture propagation; fracture geometry; non-planar propagation

Introduction

As there is plenty of coal-bedded methane in China, it is of great importance to improve the efficiency of exploration and exploitation and to adjust the energy structure[1–3]. Directional drilling together with hydraulic fracturing has become the key method for enhancing single well output in coal seams[4]. Due to the identical mechanical responses of coal seam, field operations always lead to complex fracture geometries. A lot of researches have been conducted on this topic, both domestically and internationally[5–12]. Diamond[5] and Jeffrey[6] observed the great influence of coal cleats and nature fractures on propagation paths of hydraulic fractures. Khodaverdian[7] investigated the near wellbore effect on coal bed hydraulic fracturing. Chen[8] has concluded that fracturing fluid would cause swelling of coal matrix and as a result chock the cleats leading to decreased permeability. De Peter[9] investigated the influence of bumping rates on propagation paths using samples with preset hot cracks. Abass[10] and Fan[11] also studied the propagation modes of coal seam fracturing. Fan[12] summarized three different fracture initiation and propagation modes considering coal cleats.

Laboratory tests have become the main methods of studying hydraulic fracturing for its effectiveness and intuition. But experiments of directional well fracturing in coal seals haven't been thoroughly conducted compared with that of vertical and horizontal wells. This paper proposed a new criterion for fracture initiation based on near wellbore stress field around directional wells in coal seams and analyzed factors influencing hydraulic fracture propagation. A series of true tri-axial tests have been conducted using outcrops from Linxin field, Ordos Basin and parameters were set based on similarity criterion[13–15]. Hydraulic fracture initiation and propagation in vertical wells and directional wells have been studied and compared. The influences of azimuth, in-situ stress and coal cleats on non-planar fracture propagation in directional wells have been investigated according to those experiments.

1. Criterion for hydraulic fracture initiation in coal seams

Two sets of nearly vertical coal cleats exist in natural coal rocks, namely face cleats and butt cleats, which cut the coal into small discontinuous blocks and thus compromise the integrity of coal strata. Jin[16] has proposed that cleats would affect fracture initiation and near wellbore propagation. Three initiation modes were put forward that in naturally fractured

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formations, hydraulic fractures would start from rock body, shear or tension the natural fractures. Criteria for these three modes were also analyzed.

For directional well hydraulic fracturing (Fig. 1), three principle stresses near wellbore can be described[17]:

$$\sigma_i = \frac{1}{2}\left[J - 4fp_\mathrm{p} + (4f-1)p_1\right] + \frac{1}{2}\sqrt{(K-p_1)+L} \quad (1)$$

$$\sigma_j = p_1 \quad (2)$$

$$\sigma_k = \frac{1}{2}\left[J - 4fp_\mathrm{p} + (4f-1)p_1\right] - \frac{1}{2}\sqrt{(K-p_1)+L} \quad (3)$$

where $J = (A+D)\sigma_\mathrm{h} + (B+E)\sigma_\mathrm{H} + (C+F)\sigma_\mathrm{v}$

$$K = (A-D)\sigma_\mathrm{h} + (B-E)\sigma_\mathrm{H} + (C-F)\sigma_\mathrm{v}$$

$$L = 4(G\sigma_\mathrm{h} + H\sigma_\mathrm{H} + I\sigma_\mathrm{v})^2$$

And also:

$$A = \cos\alpha\left[\cos\alpha(1-2\cos 2\theta)\sin^2\beta + 2\sin 2\beta\sin 2\theta\right] + (1+2\cos 2\theta)\cos^2\beta$$

$$B = \cos\alpha\left[\cos\alpha(1-2\cos 2\theta)\cos^2\beta - 2\sin 2\beta\sin 2\theta\right] + (1+2\cos 2\theta)\sin^2\beta$$

$$C = (1-2\cos 2\theta)\sin^2\beta$$

$$D = \sin^2\beta\sin^2\alpha + 2\upsilon\sin 2\beta\cos\alpha\sin 2\theta + 2\upsilon\cos 2\theta(\cos^2\beta - \sin^2\beta\cos^2\alpha)$$

$$E = \cos^2\beta\sin^2\alpha - 2\upsilon\sin 2\beta\cos\alpha\sin 2\theta + 2\upsilon\cos 2\theta(\sin^2\beta - \cos^2\beta\cos^2\alpha)$$

$$F = \cos^2\alpha - 2\upsilon\sin^2\alpha\cos 2\theta$$

$$G = -(\sin 2\beta\sin\alpha\cos\theta + \sin^2\beta\sin 2\alpha\sin\theta)$$

$$H = \sin 2\beta\sin\alpha\cos\theta - \cos^2\beta\sin 2\alpha\sin\theta$$

$$I = \sin 2\alpha\sin\theta$$

$$f = \delta\left[\frac{\alpha_1(1-2\upsilon)}{1-\upsilon} - \phi\right]$$

Angle between σ_i and z axis can be calculated (Fig. 1):

$$\gamma = \frac{1}{2}\arctan\frac{2(G\sigma_\mathrm{h} + H\sigma_\mathrm{H} + I\sigma_\mathrm{v})}{(A-D)\sigma_\mathrm{h} + (B-E)\sigma_\mathrm{H} + (C-F)\sigma_\mathrm{v} - p_1} \quad (4)$$

σ_i, σ_j, σ_k can be different under various pumping pressures. Here we take $\sigma_1=\max\{\sigma_i, \sigma_j, \sigma_k\}$ and $\sigma_3=\min\{\sigma_i, \sigma_j, \sigma_k\}$, three initiation modes can be recognized under distinct stress conditions.

(1) Initiation from rock body would ask for:

$$f(p_{\mathrm{f1}}) = \sigma_3 - \alpha_1 p_\mathrm{p} + S_\mathrm{t} = \frac{1}{2}\left[J - 4fp_\mathrm{p} + (4f-1)p_{\mathrm{f1}}\right] - \frac{1}{2}\sqrt{(K-p_{\mathrm{f1}})+L} - \alpha_1 p_\mathrm{p} + S_\mathrm{t} = 0 \quad (5)$$

(2) Using the principle of superposition to extend from single weak plane to multiple weak planes the theory of shear damage to coal cleats (Fig. 2):

$$\sigma_1 - \sigma_3 = \sqrt{(K-p_{\mathrm{f2}})+L} = \frac{2(C_{\mathrm{w}t} + \sigma_3\tan\varphi_{\mathrm{w}t})}{(1-\tan\varphi_{\mathrm{w}t}\cot\psi_t)\sin 2\psi_t} \quad (6)$$

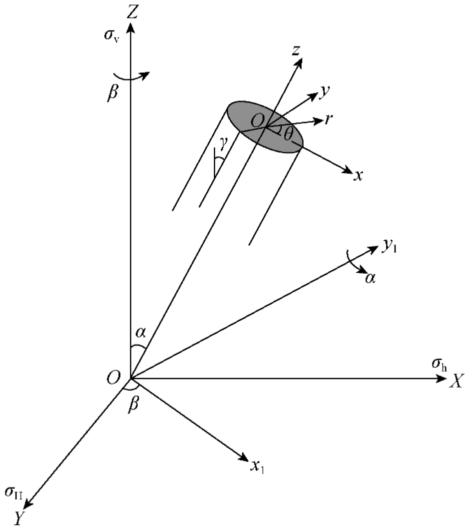
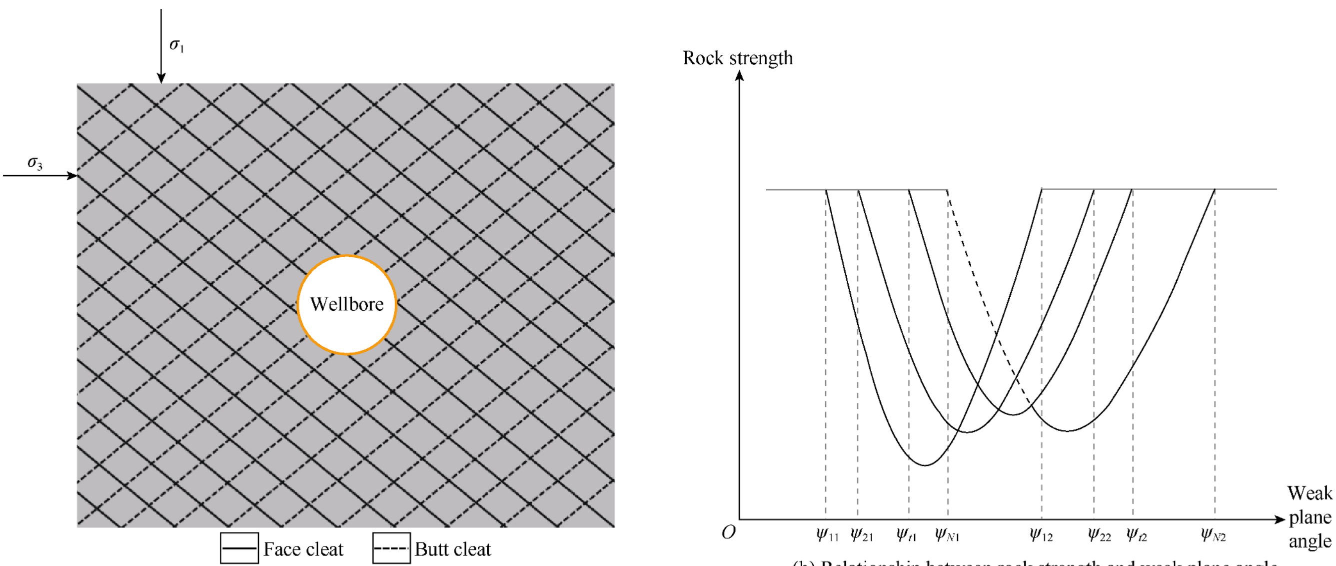


Fig. 1. Coordinate transformation for directional wells.



(a) Profile diagram of σ_1-σ_3 in coal seam

(b) Relationship between rock strength and weak plane angle

Fig. 2. Schmenatic of multiweak plane theory.