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Fracture propagation model using multiple planar fracture with mixed mode in naturally fractured reservoir

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ABSTRACT

For hydraulic fracture propagation modeling, in the past, single planar fracture approach denotes fracture propagating only in the direction perpendicular to horizontal well regardless of the existence of natural fracture. Recently, the model implements multiple planar fracture being able to describe the propagation more realistically. For fracture crossing criterion between hydraulic fracture and natural fracture, the hydraulic fracture propagation is generally assumed to be a multiple planar fracture with opening mode. This study proposes a new multi-stage hydraulic fracture propagation model using multiple planar fracture with mixed mode by linearly superposing two modes of opening and sliding. This model is then coupled with commercial reservoir flow simulator through grid mapping process in the form of discrete fracture network developed in this work. The modeling results for the verification about hydraulic fracture crossing natural fracture excellently matched with experimental results for various cases of intersection angle and maximum horizontal stress. In the investigation for inclination angle, frictional coefficient of fracture interface, and fracture orientation, hydraulic fracture passed through natural fracture appropriately corresponding to crossing criterion, and thereafter, propagated in a manner suitably consistent with respect to fracture reinitiation angle. The model of this study is compared to the model with opening mode and also the model of single planar fracture approach. The result shows that there is a large discrepancy in stimulated reservoir volume, because of a number of intersections of fracture connectivity. In the application of the model for Barnett shale reservoir, the stimulated reservoir volume of the model developed in this study and commercial model are calculated differently which indicates that the model of this study is important in evaluating the initial gas in place estimated by stimulated reservoir volume.

1. Introduction

Multi-stage hydraulic fracturing through a horizontal well (HW) is essential to economic development of shale gas reservoirs because of their extremely low permeability (Frantz and Jochen, 2005; Kim et al., 2015). The recent goal of hydraulic fracturing was not just the creation of a set of fractures in reservoirs, but also to control and guide fracture initiation, and to propagate it in an orientation that will contribute to maximum gas production (Jin et al., 2012). Fractures in homogeneous formation will propagate in direction perpendicular to minimum in situ stress direction (Whittaker et al., 1992). A horizontal well is usually designed to be parallel to the orientation of minimum in situ stress such that the fracture face induced by hydraulic fracturing can be perpendicular to the axis of borehole (Economides et al., 1989). However, the actual trajectory of hydraulic fracture (HF) frequently deviates from the designed profile due to the ratio of maximum–minimum horizontal stress and horizontal stress direction. To properly predict fracture initiation and propagation, several studies have assessed fracture initiation criteria as applied in hydraulic fracturing (Olson, 2008; Zhou et al., 2008; Chen et al., 2010; Ispas et al., 2012). From the viewpoint of practical application, three fundamental fracture criteria – maximum tangential stress, maximum energy release rate, and minimum strain energy density – appear to be used most commonly (Whittaker et al., 1992).

The presence of natural fractures in shale formation is also crucial to shale gas development (Lancaster et al., 1996). The natural fracture (NF) in shale reservoirs significantly affects the propagation trajectory of HF because of the stress distribution in NF and the frictional coefficient at fracture plane (Cooke and Underwood, 2001). The interaction between HF and NF has been investigated widely, both experimentally (Blanton, 1982; Warpinski and Teufel, 1987; Renshaw and Pollard, 1995) and numerically (Zhang and Jeffrey, 2006; Thiercelin and Makkhyu, 2007;

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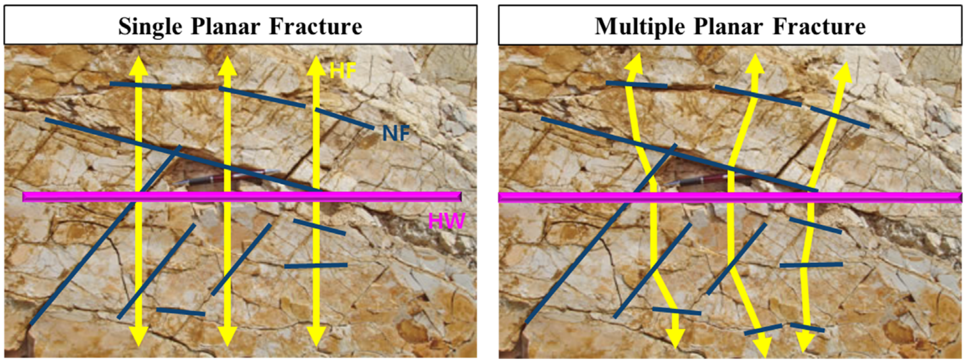

Fig. 1. Fracture propagation method.

Zhang et al., 2007; Akulich and Zvyagin, 2008). Blanton (1982) and Warpinski and Teufel (1987) derived fracture interaction criteria relating to the maximum–minimum principal stress difference on the plane of NF and the intersection angle between HF and NF. Renshaw and Pollard (1995) provided a simple criterion for crossing according only to an orthogonal interaction between HF and NF, and confirmed it in laboratory experiments. Gu and Weng (2010) extended the Renshaw and Pollard criterion to non-orthogonal intersections for practical application. This criterion was found to agree well with the experimental results. However, in previous studies, HF was assumed to be a single planar fracture (SPF), as shown in Fig. 1, which is propagated only in the direction of perpendicular to HW regardless of the presence of NF. Thus, a commercial fracture propagation model has limitations with respect to describing actual propagation (Nagel et al., 2012; Savitski et al., 2013). In order to overcome limitations and describe complex fracture geometry by NF, fracture propagation models have been developed by adopting a multiple planar fracture (MPF) approach as shown in Fig. 1. So far, previous models considered opening mode for fracture crossing criterion between HF and NF. This is reasonable only when HF encounters NF orthogonally. However, when HF encounters NF non-orthogonally, the tip of HF slips to elastic region along the NF face, and then propagate through rock mass, corresponding to the stress difference between HF tip and NF face. Therefore, in such cases, it is essential to include the sliding mode which is caused by shear stress acting parallel to the NF face (Fig. 2).

Therefore, we proposed a new HF propagation model in naturally fractured shale reservoir to describe the fracture propagation, more realistically, using MPF approach with mixed mode, unlike conventional hydraulic fracturing model employed with SPF. This propagation model was coupled with a commercial reservoir flow simulator 「GEM」 from Computer Modelling Group (CMG) through grid mapping process in the form of discrete fracture network developed in this work.

2. Model development

The governing equation, which includes the stress intensity factor (SIF) for fractures of opening mode (K_I, $\mathrm{MPa}\cdot\mathrm{m}^{1/2}$) and sliding mode (K_{II}, $\mathrm{MPa}\cdot\mathrm{m}^{1/2}$) simultaneously, for the stress field near the fracture tip. In this equation, two modes are linearly superposed, based on the theory of linear elastic fracture mechanics.

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix}=\begin{bmatrix}\sigma_H\\ \sigma_h\\ 0\end{bmatrix}+\frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\begin{bmatrix}1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\\ 1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\\ \sin\frac{\theta}{2}\cos\frac{3\theta}{2}\end{bmatrix}+\frac{K_{II}}{\sqrt{2\pi r}}\sin\frac{\theta}{2}\begin{bmatrix}-\left(2+\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right)\\ \cos\frac{\theta}{2}\cos\frac{3\theta}{2}\\ \cot\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\end{bmatrix}, \tag{1}$$

where σ_x and σ_y are normal stresses to x- and y-direction near crack tip (MPa), τ_{xy} is the shear stress on x–y plane (MPa), σ_H and σ_h are maximum and minimum horizontal stresses (MPa), r is the radial distance to crack tip (m), and θ is the polar angle to direction of crack tip (deg).

The stress intensity factors for opening and sliding modes are defined as follows (Jin and Shah, 2013):

$$K_I=\left(P+\delta_1 p-\sigma_H\sin^2\alpha-\sigma_h\cos^2\alpha\right)\sqrt{\pi D}, \tag{2}$$

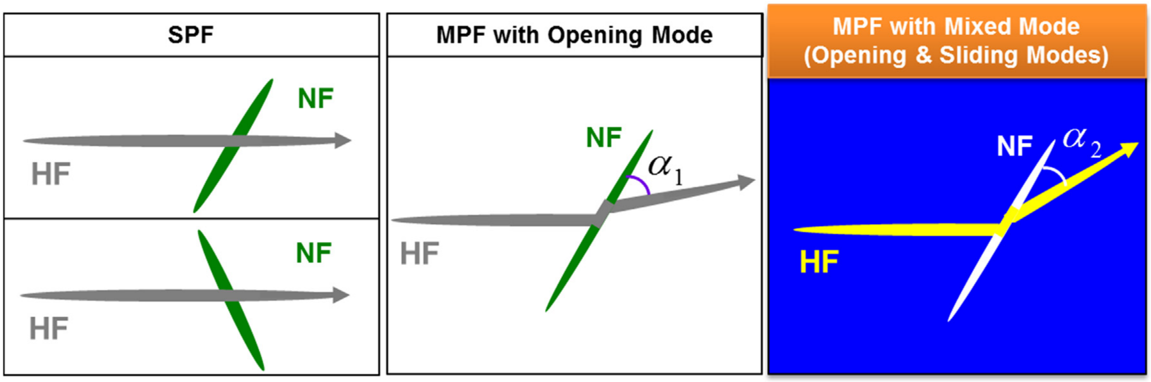

Fig. 2. Fracture crossing aspect depending on three different approach.