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Seepage-stress coupling mechanism for intersections between hydraulic fractures and natural fractures

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ABSTRACT

Most unconventional oil and gas reservoirs contain some natural fractures, which play an essential role during reservoir reconstruction. Given the strong discontinuities in the displacement on both sides of the fracture as well as weak discontinuities in the pore fluid pressure, a novel three-dimensional seepage-stress coupling model using extended finite element method is proposed for fractured reservoirs. This directly coupled scheme for displacement field and stress field avoids the cumbersome process during calculating the fluid pressure in complicated fracture networks and translating into equivalent nodal force. Numerical examples are presented to simulate the fracture propagation pathway during the laboratory experiment on the staged synchronous fracturing of a horizontal well, revealing the deformation response and interaction mechanism between hydraulic fractures and natural fractures at orthotropic and non-orthotropic angles. The results show that due to the stress shadow effects, a non-planar fracture deflecting to wellbore would be formed during the progress of staged synchronous fracturing for a horizontal well. Moreover, the adjacent section to the intersection is opened and the others are closed for orthogonal natural fracture. In contrast, the non-orthogonal natural fracture is activated near the intersection at first and then fully opens as time increases; eventually, it is in the tensile-shear and composite state. In other words, the hydraulic fracture tends to traverse the orthogonal natural fracture and continue to propagate, as it is more easily arrested by the oblique natural fracture and transferred to propagation.

1. Introduction

Most unconventional reservoirs such as gas shales have dense matrices containing extensively developed natural fractures (Gale et al.). Reservoir stimulation drives these natural fractures to expand continuously and introduces shear slip in brittle rocks, thus forming complicated networks of intersecting natural fractures and artificial fractures that further increase the transformed volume (Zuo et al., 2010). Therefore, the volume stimulation method becomes one of the key technologies in unconventional oil and gas development (Qi et al., 2012). However, the interactions during volume stimulation between geological discontinuities such as fracturing fluid, rock matrix and natural fractures are extremely complicated, as are the mechanical behaviors before, during and after the intersections between extended, hydraulically induced fractures and pre-existing natural fractures. Because of these factors, the real-time simulation of complicated fracture propagation during volume fracturing is very difficult (Fu et al., 2013; Liqiang et al., 2014).

The morphology of complicated fracture networks created by volume fracturing can be estimated by determining the mechanical mechanism and propagation behavior of hydraulically induced fractures before, during and after intersecting with natural fractures. In laboratory experiments, a true triaxial fracturing simulation system can be used in combination with high-energy CT scanning, acoustic emission and microscopic X-ray chromatography to characterize the intersection behavior between hydraulically induced fractures and natural fractures during the fracturing of artificial rock or reservoir outcrop rock samples.

These methods also reveal the influences of crustal stress state, horizontal principle stress difference, approach angle, natural fracture interface properties, injection fluid amount and fracturing fluid viscosity (Guo et al., 2014; Jian et al., 2008a, 2008b; Mian et al., 2008;

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Mohammad, 2012). Scholars have developed a series of criteria to describe the intersection behavior between hydraulic fractures and natural fractures. For example, Renshaw and Pollard proposed a criterion for the intersection between hydraulic fractures and orthogonal fractures (R-P criterion) (Renshaw and Pollard, 1995). Gu and Weng expanded the R-P criterion to encompass non-orthogonal conditions (G-W criterion) by considering that the approach angles of hydraulic fractures and natural fractures are between 0° and 90° (Gu et al., 2012). Meanwhile, Chen Wan et al. considered the dip angle of natural fractures and expanded the R-P criterion to three dimensional conditions (Wan et al., 2014). Taleghani investigated the tensile property and shearing behavior of natural fractures while hydraulic fractures are approaching but before they come into contact (Taleghani and Olson, 2011). All of these criteria only consider the mechanical behavior caused by the interaction between hydraulic fractures and natural fractures, without accounting for the influence of the hydraulic effect induced by the injection of fracturing fluid.

Fang Shi (Shi et al., 2017) established an XFEM-based coupled method and the continuity of pressure and the mass balance at intersections of hydro-fractures are automatically achieved by sharing a common fluid node in the coupled method. Besides, the contact behavior of frictional fractures is modeled with penalty method within the framework of plasticity theory of friction. Moreover, extended Renshaw and Pollard criterion is utilized to predict whether a hydro-fracture will propagate across the frictional fracture. TaoWang and Zhanli Liu (Wang et al., 2017) develop a XFEM model coupling Biot theory to study the interaction between hydraulic fracture and natural fracture, in the model, the fluid flow is solved in a unifed framework by considering the fractures as a kind of special porous media and introducing Poiseuille-type flow inside them instead of Darcy-type flow. A weak formulation is derived based on virtual work principle, which includes the XFEM formulation for multiple fractures and fractures intersection in porous media and finite element formulation for the unifed fluid flow. Then the plane strain Kristianovic-Geertsma-deKlerk (KGD) model and the fluid flow inside the fracture network are simulated to validate the accuracy and applicability of this method.

At present, many scholars have done a lot of meaningful research on the intersecting effect of hydraulic fractures and natural fractures. However, there are few reports on the coupling of seepage and stress, and most scholars consider the intersecting between a hydraulic cfracture with one natural fracture, this is a relatively simple case. This paper adopts the extended finite element method (XFEM) to establish the seepage-stress coupling mathematical model of fractured-rock-mass multi-phase-fluid. This decision is based on the strong discontinuity of displacement at either side of fractures and the weak discontinuity of pore-fluid pressure, as XFEM represents the most commonly used method in simulating discontinuous media, the XFEM model are used to calculate the pressure distribution when there are multiple fractures and tracing the hydraulic fracture extension path. This paper also discusses the deformation response features and mechanical mechanisms at work while injecting fracturing fluid before the intersection occurs between hydraulically induced fractures and orthogonal and oblique natural fractures.

2. Three-dimensional seepage - stress coupling model

The seepage-stress coupling model consists of two parts: the ***Solid rock deformation*** part calculates the solid deformation and the crack propagation; the ***Fluid flow*** part computes the fluid flow process. The process of the two iterated modules is shown in Fig. 1:

2.1. Control equation of three - dimensional seepage-stress coupling

Fig. 2 shows a bounded control body $\Omega \subset \mathbb{R}n$ $(n = 2, 3)$ with an outer boundary of Γ.

The effective stress equilibrium equation is as follows:

$$\nabla\cdot\boldsymbol{\sigma} + \rho\boldsymbol{g} = \nabla\cdot(\boldsymbol{\sigma}' - \alpha\boldsymbol{I}p) + \rho\boldsymbol{g} = 0 \tag{1}$$

The flow continuity equation for the wetting phase fluid in the matrix is as follows:

$$\begin{aligned}&\left[\frac{\alpha-\phi}{K^s}S_m^w\left(S_m^w+\frac{p_m^c\partial S_m^w}{\partial p_m^c}\right)+\frac{\phi S_m^w}{K^w}-\frac{\phi\partial S_m^w}{\partial p_m^c}\right]\frac{\partial p_m^w}{\partial t}\\&\quad+\left[\frac{\alpha-\phi}{K^s}S_m^w\left(S_m^{nw}-\frac{p_m^c\partial S_m^w}{\partial p_m^c}\right)+\frac{\phi\partial S_m^w}{\partial p_m^c}\right]\frac{\partial p_m^{nw}}{\partial t}\\&+\alpha S_m^w\boldsymbol{I}^T\frac{\partial\varepsilon}{\partial t}+\nabla\cdot\left(-\frac{\boldsymbol{k}_m k_{m,rw}}{\mu^w}\nabla p_m^w\right)+Q_{wstc}B_w=0\end{aligned} \tag{2}$$

The flow continuity equation for the non-wetting phase fluid in the matrix is as follows:

$$\begin{aligned}&\left(\frac{\alpha-\phi}{K_s}S_m^g\left(S_m^w+\frac{p_m^c}{\phi_m}C_m^s\right)+C_m^s\right)\frac{\partial p_m^w}{\partial t}\\&\quad+\left[\frac{\alpha-\phi}{K_s}S_m^g\left(S_m^g-\frac{p_m^c}{\phi_m}C_m^s\right)+\frac{\phi_m S_m^g\rho^{gsc}T_{sc}}{\rho^g ZTp_{sc}}\left(1-\frac{p_m^g}{Z}\right)-C_m^s\right]\frac{\partial p_m^g}{\partial t}\\&+\alpha_m S_m^g\mathbf{I}_m^T\frac{\partial\varepsilon}{\partial t}+\nabla\cdot\left(-\frac{\mathbf{k}_m k_{m,rg}}{\mu_g}\nabla p_m^g\right)=0\end{aligned} \tag{3}$$

The flow continuity equation of the wetting phase fluid in the fractures is as follows:

$$\left(\frac{S_f^w}{K^w}-\frac{\partial S_f^w}{\partial p_f^c}\right)\frac{\partial p_f^w}{\partial t}+\frac{\partial S_f^w}{\partial p_f^c}\frac{\partial p_f^{nw}}{\partial t}+\nabla\cdot\left(-\frac{k_f k_{f,rw}}{\mu^w}\nabla p_f^w\right)+S_f^w\nabla\cdot\dot{\boldsymbol{u}}=0 \tag{4}$$

The flow continuity equation of the non-wetting phase fluid in the fractures is as follows:

$$\begin{aligned}&C_f^s\frac{\partial p_f^w}{\partial t}+\left[\frac{S_f^g\rho^{gsc}T_{sc}}{\rho^g ZTp_{sc}}\left(1-\frac{p_f^g}{Z}\right)-C_f^s\right]\frac{\partial p_f^g}{\partial t}+S_f^g\nabla\cdot\dot{\mathbf{u}}+\nabla\\&\quad\cdot\left(-\frac{k_f k_{f,rg}}{\mu_g}\nabla p_f^g\right)=0\end{aligned} \tag{5}$$

The displacement and pore pressure of the wetting phase fluid and non-wetting phase fluid at t = 0 are provided according to the initial conditions.

$$\begin{aligned}&\boldsymbol{u}=\boldsymbol{u}^0\\&p_m^w=p_m^{w,0}\\&p_m^g=p_m^{g,0}\end{aligned} \tag{6}$$

The displacement and pore pressure of the wetting phase fluid and non-wetting phase fluid at the boundary are provided by the forced boundary conditions.

$$\begin{aligned}&\boldsymbol{u}(\boldsymbol{x})=\tilde{\boldsymbol{u}}\quad\forall\,\boldsymbol{x}\in\Gamma_u^u\\&p_m^w(\boldsymbol{x})=\tilde{p}_m^w\quad\forall\,\boldsymbol{x}\in\Gamma_p^w\\&p_m^g(\boldsymbol{x})=\tilde{p}_m^g\quad\forall\,\boldsymbol{x}\in\Gamma_p^g\end{aligned} \tag{7}$$

The stress and mass flow rate of the wetting phase fluid and non-wetting phase fluid at the boundary are provided by the forced boundary conditions.

$$\begin{aligned}&\boldsymbol{\sigma}(\boldsymbol{x})\cdot\boldsymbol{n}=\tilde{\boldsymbol{t}}\quad\forall\,\boldsymbol{x}\in\Gamma_u^t\\&\left(-\frac{\boldsymbol{k}_m k_{m,rw}}{\mu^w}\nabla p_m^w\right)\cdot\boldsymbol{n}=\frac{\tilde{q}^w}{\rho^w}\quad\forall\,\boldsymbol{x}\in\Gamma_q^w\\&\left(-\frac{\boldsymbol{k}_m k_{m,rg}}{\mu^{nw}}\nabla p_m^{nw}\right)\cdot\boldsymbol{n}=\frac{\tilde{q}^g}{\rho^g}\quad\forall\,\boldsymbol{x}\in\Gamma_q^g\end{aligned} \tag{8}$$

A fluid pressure is applied on the fracture surface.

$$\begin{aligned}&\boldsymbol{\sigma}(\boldsymbol{x})\cdot\boldsymbol{n}_{\Gamma_f^+}=\left(S_f^w p_f^w+S_f^g p_f^g\right)\cdot\boldsymbol{n}_{\Gamma_f}\quad\forall\,\boldsymbol{x}\in\Gamma_f^+\\&\boldsymbol{\sigma}(\boldsymbol{x})\cdot\boldsymbol{n}_{\Gamma_f^-}=-\left(S_f^w p_f^w+S_f^g p_f^g\right)\cdot\boldsymbol{n}_{\Gamma_f}\quad\forall\,\boldsymbol{x}\in\Gamma_f^-\end{aligned} \tag{9}$$

The pore fluid pressure at the fracture boundary is continuous, with