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Numerical simulation of elasto-plastic hydraulic fracture propagation in deep reservoir coupled with temperature field

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ABSTRACT

With the increasing demand of oil and gas resource, the development of deep reservoir has become an inevitable trend. To investigate the coupled effects of rock elasto-plastic deformation, fluid flow and heat transfer in the process of hydraulic fracturing of deep reservoir, the mathematical model of elasto-plastic hydraulic fracture propagation is established based on cohesive zone model (CZM) and embedded discrete fracture model (EDFM). The constitutive equation incorporating thermal stress is derived by using Drucker-Prager yield condition and the associated flow law. Fluid flow in the fracture is modeled with lubrication theory. The thermal non-equilibrium theory is employed to describe the heat exchange between rock matrix and fluid in the fracture based on EDFM. The CZM is used as fracture propagation criterion. The rock deformation equation is solved by finite element method. The temperature field and fluid flow in the fracture are discretized by finite volume method. Due to the non-linearity of flow equation, the iterative method is used to solve the coupled problem of stress, pressure and temperature fields. A Triangular-PEBI (Perpendicular Bisector) dual mesh system is presented for numerical implementation. The numerical model is validated against with analytical solution and other methods in the literature. The results show the significance of accounting for elasto-plastic deformation and heat transfer when simulating hydraulic fracture propagation in deep reservoir.

1. Introduction

Along with the increasing demand of oil and gas resource all over the world, it is more and more difficult to make major breakthrough on the exploration of gas and oil in middle or shallow basins. The development of deep reservoir has become an inevitable trend (Pang et al., 2015). The characteristics of high temperature, high pressure and high in-situ stress in deep reservoirs make rock deform from elasticity to plasticity (Chen, 2004). Therefore, large-scale yielding of rock may take place in the process of hydraulic fracturing in deep reservoir, which means the theory of linear elastic fracture mechanics (LEFM) is no longer applicable to simulate fracture propagation. Besides, heat transfer in the formation can't be ignored due to the large temperature difference between rock and fracturing fluid. Therefore, new models are needed to adequately simulate hydraulic fracture propagation in deep reservoir.

With the exploitation of shale gas, numerical simulation of hydraulic fracture propagation has become a hot issue in scholars' researches (Dahi Taleghani, 2009; Morgan and Aral, 2015; Zeng and Yao, 2016; Zeng et al., 2018). But these studies mainly focus on elastic fracture propagation. Few of them accounts for elasto-plastic behavior of rock during fracture propagation. Papanastasiou (1997, 1999a, 1999b) established a model for fluid-driven fracture propagation based on Mohr-Coulomb yield criterion and solved the model by using FEM/FDM. Bigoni and Radi (1993) and Radi et al. (2002) presented near-tip asymptotical solutions based on Druker-Prager yield condition with both of associative and non-associative flow laws. Sarris and Papanastasiou (2013) extended Papanastasiou's model for fracture propagation in poro-elasto-plastic continuum. Wang (2016) presented a coupled poro-elasto-plastic model for hydraulic fracture propagation based on extended finite element method (XFEM). However, heat transfer is not considered during hydraulic fracturing in these studies.

Recently, the thermal effect on hydraulic fracture propagation has attracted lots of attentions. Tomac and Gutierrez (2016) studied the coupled problem of THM in the process of hydraulic fracturing based on bonded particle model (BPM). Feng et al., 2016 introduced a new thermal module and incorporated it into the simulator FLAC3D to study heat transport and THM coupled processes during hydraulic fracturing in shale formation. Kim and Moridis (2013) developed a T + M simulator by coupling a flow simulator to a geomechanics code. Subjects

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in these researches are elastic rock without considering elasto-plastic behavior.

The criterions for fracture propagation based on LEFM are not applicable to elasto-plastic fracture propagation. Dugdale (1960) and Barenblatt (1962, 1959) proposed CZM by investigating fracture tip with small scale of plasticity. Now, CZM has been adopted by some researchers to simulate fracture propagation. Boone et al. (1986) and Boone and Ingraffea (1990) early used CZM to model fracture propagation. Chen (2012) simulated hydraulic fracture propagation in penny-shape model by using CZM. Sarris and Papanastasiou (2012, 2011) modeled a plain strain hydraulic fracture in elastic and elasto-plastic formation. Gonzalez-Chavez et al. (2015) developed a cohesive model to simulate hydraulic fracturing in naturally fractured formation.

The paper is organized as follows. Section 2 describes governing equation of hydraulic fracture propagation, including elasto-plastic deformation, fluid flow and heat transfer parts. Section 3 presents an efficient numerical algorithm with a Triangular-PEBI (Perpendicular Bisector) dual mesh system. Section 4 validates the numerical model by comparing with analytical solutions and other methods. Section 5 analyzes the characteristics of stress, pressure and temperature fields in the process of hydraulic fracturing in details. Section 6 draws some conclusions.

2. Model description

Based on the classical plane strain fracture geometry, the model is developed as shown in Fig. 1. It is assumed that the horizontal well is drilled in the direction of minimum stress, and the direction of fracture initiation is perpendicular to the wellbore. In the process of fracture propagation, plastic deformation of rock may take place due to the stress concentration near the fracture tip caused by fluid pressure, temperature variation and in-situ stresses. There are four important coupling processes involved in hydraulic fracturing in deep reservoir: (i) rock deformation induced by fluid pressure and temperature variation; (ii) fluid flow in the fracture; (iii) heat transfer between rock and fracturing fluid; (iv) fracture propagation. Therefore, the mathematical model includes four parts: (1) elasto-plastic deformation equation; (2) non-linear fluid flow equations; (3) temperature field equation; (4) propagation criterion.

2.1. Deformation field equation

In the process of fracture propagation, rock deformation near fracture tip is in plastic state due to stress concentration. The behavior of the rock must be described by plastic theory. And thermal stress caused by the injection of low-temperature fracturing fluid must be considered.

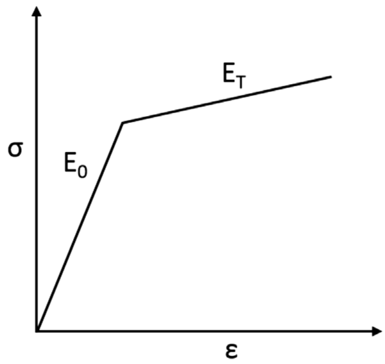

Fig. 2. Stress-strain curve of linear hardening elasto-plastic model.

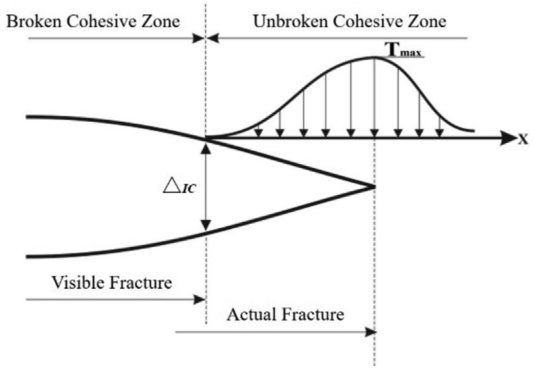

Fig. 3. Schematic diagram of cohesive zone.

2.1.1. Equilibrium equation

$$\sigma_{ij,j} + F_i = 0 \tag{1}$$

where σ_{ij} is stress tensor, F_i is the body force per unit volume in the i-coordinate ($i = x, y$ in 2D).

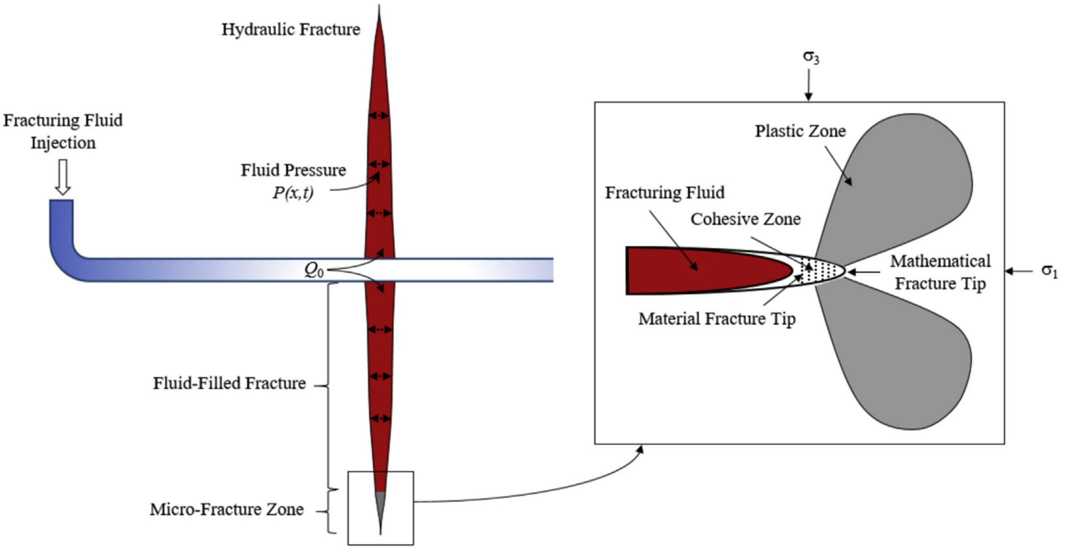

Fig. 1. Illustration of the plane strain hydraulic fracture in elasto-plastic formation.