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Numerical simulation of fracture network generation in naturally fractured reservoirs

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ABSTRACT

In this study, numerical modeling of hydraulic fractures propagation is performed to analyze the forming mechanism of complex fracture network during the process of hydraulic fracturing in naturally fractured reservoirs. The model couples fracture deformation with fluid flow in the fracture network and horizontal wellbore. The enhanced 2D displacement discontinuity method is used to capture fracture deformation. When fracturing fluid fills the natural fracture before crossing happens, the interaction criterion between hydraulic fracture and natural fracture developed by Gu et al. (2012) is modified to incorporate fluid pressure in natural fracture. The implicit level set schemes based on tip asymptotical solution is presented to locate the fracture tips. Simulation results indicate that fracture spacing and stress anisotropy have significant influence on the propagation path and geometry of multiple fractures. Accounting fluid pressure drop in the wellbore will lead to asymmetrical geometry and stress shadowing effect of side fractures on the middle fracture when three-cluster fractures propagate simultaneously. Multiple fractures will be directed back to the maximum stress direction after long propagation length. Results show that stress shadowing effect and natural fractures are key controlling factors of complex fracture networks in unconventional reservoirs.

1. Introduction

Horizontal well drilling and hydraulic fracturing have become key technologies in the development of shale gas reservoirs. The application of hydraulic fracturing is also essential for other tight sand reservoirs and hot dry rock (HDR) geothermal systems. The complexity of fracture network is closely related to the geological complexity of formation, including the existence of natural fractures, anisotropy of stress and heterogeneity of rock properties. The conventional bi-wing fracture models (Perkins and Kern, 1961; Geertsma and Klerk, 1969; Khristianovic and Zheltov, 1955) are not able to predict the induced hydraulic fracture network; therefore new models are needed to adequately simulate the hydraulic fracture network propagation in unconventional reservoirs.

Simulation of hydraulic fracture propagating in a formation with pre-existing natural fractures is very complex, which requires proper consideration of key physical elements, including rock deformation, fracture propagation, fluid flow in the fracture networks, fracture height growth, interaction between hydraulic and natural fractures, interaction among adjacent hydraulic fractures and proppant transport in the fracture networks (Weng, 2015). In recent years, a great number of hydraulic fracture models have been developed for simulating induced complex fracture networks in unconventional reservoir. Xu et al. (2010) proposed Wire-mesh to model the hydraulically induced fracture networks that consist of two orthogonal sets of parallel and uniformly spaced fractures. Meyer and Bazan (2011) presented MShale model based on discrete fracture network, which was similar to Wire-mesh model. The researchers from Schlumberger (Weng et al., 2011; Kresse et al., 2013) developed unconventional fracture model (UFM) to simulate propagation of complex fractures in naturally fractured formation. In their models, the stress shadow effect and the interaction between hydraulic fractures and natural fractures were considered and analyzed. McClure (2012) developed a comprehensive 2D displacement discontinuity method (DDM) based model fully coupled with fluid flow, stresses induced by fracture opening and sliding, friction evolution, and fracture propagation in a pre-existing discrete fracture network (DFN). Fu et al. (2013) presented an explicitly integrated, fully coupled discrete-finite element approach for the simulation of hydraulic

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fracturing in arbitrary fracture networks. Wu and Olson (2014) developed a fracture-propagation model (FPM) based on enhanced displacement discontinuity method with a correction factor to account for the effect of finite fracture height to simulate multiple hydraulic fracture propagation from a horizontal well. They have also extended their models by accounting for natural fractures to simulate complex hydraulic fracture development in natural fractured reservoirs (Wu and Olson, 2015). Xu and Wong (2013) and Wong et al. (2013) presented 3D boundary element based model for simulating multiple fractures propagating from perforation clusters and effect of stress shadowing on sequentially placed fractures. Guo and Liu (2014) developed a comprehensive model for simulating fracturing fluid leak off in natural fractures. Moreover, Weng (2015) presents a general overview of hydraulic fracturing models developed and applied to the simulation of complex fracture networks in naturally fractured formation.

Recently, the extended finite element method (XFEM) has been introduced to solve fracture propagation problem. By using XFEM approach, fractures are allowed to propagate independently of the mesh configuration, which means no need for re-meshing. Moreover, adding additional degrees of freedom for the enriched elements around the fractures eliminates the need for mesh refinement. Lecampion (2009) used XFEM to solve single hydraulic fracture propagation problem. Ren et al. (2009) explored numerical modeling for concrete hydraulic fracturing with the extended finite element method by assuming that water pressure is constant and imposed on the fracture surfaces. Dahi-Taleghani and Olson (2011) presented XFEM model to simulate hydraulic fracture intersecting natural fractures. Gordeliy and Peirce (2013) presented XFEM schemes for modeling fluid driven fractures, which exploit an implicit level set algorithm for locating the fracture tips. Those applications of XFEM described above in modeling hydraulic fracture propagation are just in the start-up stage, but they have shown great promise, especially for coupled geomechanics and reservoir models.

To summarize what has been mentioned above, Wong et al. (2013) mainly focused on the geomechanical interaction of multiple hydraulic fractures in horizontal wells, whose model can handle the true 3D fracture propagation and has many applications in shale reservoirs. In their models, the impact of natural fractures was briefly discussed. Those models (Xu et al., 2010; Meyer and Bazan, 2011) used regular geometry as equivalent representation of hydraulically induced fracture network, which didn't directly account for the process of hydraulic fractures intersecting natural fractures. Nevertheless the models had the advantages of fast computation speed due to semi-analytical solution. Other models (Fu et al., 2013; Dahi-Taleghani and Olson, 2011; Gordeliy and Peirce, 2013) used finite element method or XFEM to solve hydraulic fracture propagation problem, whose computation time was too long for field application. The models (Weng et al., 2011; McClure, 2012) used DDM to account for stresses induced by fracture displacement discontinuities, whose computation speed was much faster than finite element method. However, these models didn't account for the pressure drop in the wellbore and advanced fracture tips with an explicit method. The model proposed in this study adopts displacement discontinuity method, but differs from previous models that it accounts for pressure drop in the wellbore and advances fracture tips with an implicit level set algorithm. The displacement discontinuity method has the advantage of fast computation speed, and implicit level set algorithm has the advantage of unconditional convergence. The model combines the both benefits.

The interaction between hydraulic fracture and natural fracture is a critical factor for complex fractures model. When a hydraulic fracture approaches a natural fracture it can propagate across or be arrested by the natural fracture, and can subsequently open the natural fracture. Extensive theoretical and experimental work as well as numerical simulations has been done to investigate the interaction between hydraulic fracture and natural fracture over the last decades. Blanton (1986) presented an experimental study to analyze the effect of interaction angle and differential stress on the hydraulic fracture propagation. Warpinski and Teufel (1987) performed mineback experiments to investigate the effect of geologic discontinuities on the hydraulic fracture propagation, and figured out three modes of induced fracture propagation, including crossing, arrest by opening the joint and arrest by shear slippage of joint. Renshaw and Pollard (1995) developed a simple criterion for predicting if a fracture will propagate across a frictional interface orthogonal to the fracture. Potluri et al. (2005) reviewed various fracture interaction criteria and presented a systematic study to analyze the effect of natural fractures on hydraulic fracture propagation. Gu et al. (2012) extended the Renshaw and Pollard criterion to fracture intersection at non-orthogonal angles. Recently, Chuprakov et al. (2013) developed a new analytical model (OpenT) that takes into account the mechanical influence of the hydraulic fracture opening and the hydraulic permeability of the natural fracture and showed that fluid injection parameters such as the injection rate and the fluid viscosity are of first-order in the crossing behavior.

The paper is organized as follows. Section 2 presents problem formulations for hydraulic fracturing problem, including model description, governing equations, tip asymptote and interaction between hydraulic fracture and natural fracture. The enhanced displacement discontinuity method is used to capture fracture deformation. The mathematical models of fluid flow in fracture network and wellbore are established respectively. Gu et al. (2012) criterion is modified to incorporate fluid pressure for natural fracture in the interaction between hydraulic fracture and natural fracture. Section 3 describes details of the numerical algorithms, including iterative solution of coupled equations to solve for fracture growth length. Section 4 demonstrates the performance of the algorithm by comparison with explicit method for an hydraulic fracture propagation problem, and analyzes the results of simultaneous propagation of multiple hydraulic fractures and the effect of natural fractures. Section 5 draws some concluding remarks.

2. Problem formulations

2.1. Hydraulic fractures propagation model

Consider multiple hydraulic fractures propagating from horizontal well as shown in Fig. 1. The assumptions of the numerical model include: 1.the horizontal well is parallel to minimum horizontal principal stress direction and perforated for multiple clusters; 2.the fractures initiate in the direction perpendicular to the wellbore; 3.the deformation and rupture of rock mass due to injection of fracturing fluid is elastic; 4.the fracturing fluid is Newtonian fluid, and it can be extended to power-law fluid; 5.there is no proppant effect in the fluid pressure calculation; 6.fracture tips advance in accordance to tip asymptote solution.

The limitation of the model is that heights of fractures are fixed, both for hydraulic and natural fractures. When accounting for the interaction of hydraulic fracture and natural fracture, the fixed finite height of fractures may cause inaccuracy to the simulation result.

2.2. Governing equations

Because of stress shadowing effect, the fracture propagation direction and geometry differs from each other, which needs to be solved by coupling fracture deformation and fluid flow.