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Numerical simulation of simultaneous multiple fractures initiation in unconventional reservoirs through injection control of horizontal well

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ABSTRACT

Simultaneous fracturing stimulations in horizontal well are effective tools for promoting productivity of unconventional reservoirs. However, fracture lengths and widths of some perforation clusters may be restricted due to the stress shadow effects. In this paper, a numerical model to simulate nonplanar fractures simultaneous initiation in porous media is established based on the extended finite element method (XFEM). The amount of fluid flowing into each fracture is dynamically calculated with a total injection volume in this model. Sensitivity studies of formation parameters on fractures geometry of simultaneous fracturing are presented. The in-situ stress contrast is found to be the main factor controlling the fractures propagation. The initiation of interior fracture will be restricted or compressed to be closed in the vicinity of the injection point. The influence of injection rate and perforation friction on fractures initiation is investigated. Strategies to optimize fractures geometry are presented through injection control of each fracture. The method presented in this paper can be used in horizontal well design to achieve reasonable fractures geometry.

1. Introduction

Multiple hydraulic fracturing treatments in horizontal well significantly improve reservoirs productivity (Pope et al., 2010; Chaudhri, 2012; Yu and Sepehrnoori, 2013). For simultaneous fracturing, several clusters are grouped into a fracture treatment stage that are all stimulated at once to create similar fractures from each cluster. Several studies shown that approximately 80% of the production generally comes from 20% of the clusters, while approximately 30% of the clusters do not produce at all due to the variability of the formation and mechanical interaction between fractures (Baihly et al., 2007; Miller et al., 2011). Strategies for effective stimulation of multiple perforation clusters in horizontal well to improve production are significant for practical engineering. Simulation and optimization of multiple fractures stimulation have been investigated by many researchers. Finite element models based on cohesive zone method were developed to simulate simultaneous fractures initiation in horizontal well (Shin and Sharma., 2014; Guo et al., 2015; Haddad and Sepehrnoori, 2015a,b). However, fractures initiation paths have to be predefined in those models. Settgast et al. (2015) use a Finite Element Method (FEM) based model to investigate simultaneous fracturing. Perforation friction and uneven spacing between clusters are investigated. However, fracture surfaces are restricted to be planar and the perforation friction is a constant during stimulation process. Sesetty and Ghassemi (2015) investigate the simulation of sequential and simultaneous hydraulic fracturing in single and multi-lateral horizontal wells using displacement discontinuity method (DDM). The fluid is distributed into fractures based on their transmissibility and the injection rate into each fracture is part of the solution of the presented model. Wu and Olson (2015) developed a DDM model to account for the fluid flow in horizontal well and perforations to simulate multiple fractures initiation with simultaneous injection method. Multiple fractures initiation in naturally fractured horizontal well was established (Olson and Taleghani, 2009). Planar-3D (Bunger and Peirce, 2014) and Pseudo-3D (Kresse et al., 2013; Weng et al., 2014) models to simulate the initiation of simultaneously generated fractures have been presented. In addition, the initiation of nonplanar-3D model based on DDM has been developed (Kumar and Ghassemi, 2016). In unconventional oil and gas reservoirs, the initiation of hydraulic fractures will change formation pore pressure. The previous DDM-based models do not incorporate the

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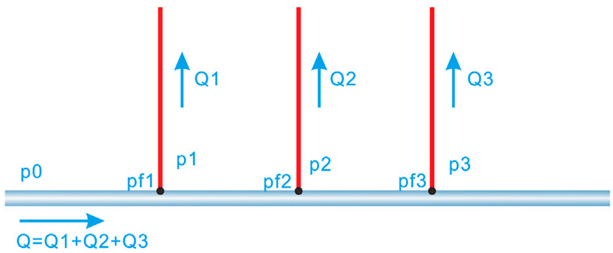

Fig. 1. Schematic representation of fluid distribution for multiple perforation clusters in a horizontal well (a half of the model).

variations of pore pressure in the formation. And the rock matrix constitutive is limited to be linear elastic. The XFEM is an effective numerical method to simulate nonplanar hydraulic fractures growth without remeshing. The method can introduce more complex constitutive models to simulate mechanical behavior of rock matrix. The initiation of hydraulic fractures and its interaction with natural fractures has been addressed by the models based on XFEM (Dahi-Taleghani and Olson, 2011; Keshavarzi and Jahanbakhshi, 2013). Models to simulate fracture initiation in fluid-filled porous media based on XFEM were developed (Mohammadnejad and Khoei, 2013a, 2013b; Mohammadnejad and Andrade, 2016). Shi et al. (2016) built a coupled extended finite element approach for modeling sequentially generated fractures in consideration of proppant. Haddad and Sepehrnoori (2015a,b) investigated multiple fractures initiation in quasi-brittle shale formations using an XFEM-based cohesive zone model. The nonplanar fractures initiation in porous media is incorporated in their model. However, the fracturing fluid injected into each fracture is assumed to be a constant. The dynamic distribution of fracturing fluid into each fracture based on XFEM in porous media has not been presented yet. Lecampion and Desroches (2015) presented a planar fractures model considering stress interaction and the local pressure drop caused by fluid partitioning to study fractures length for varying parameters. Further, they studied the effect of the variations of in-situ stress along horizontal well on fracture length (Lecampion et al., 2015). The previous results focus on creating an even length of the fractures to promote production. However, the interaction between fractures affects both fracture length and width. The proppant cannot be injected into the fractures of small width or partially closed in a stage, which will result in low performance of the production. Miller et al. (2011) investigated the production log data from over 100 horizontal wells in different reservoirs and found that reducing perforation cluster spacing will lead to higher productivity. Strategies to minimize fracture spacing in horizontal well completions have been studied in the literature (Roussel and Sharma, 2011; Guo et al., 2015). However, a low fracture spacing can cause strong mechanical interaction between fractures, and results in unexpected fractures geometry (Roussel and Sharma, 2011; Guo et al., 2015; Liu et al., 2016). Successfully completions of horizontal well need to create fractures that have approximate equality length and allow proppant to be injected with low fracture spacing. How to adjust stimulation parameters to achieve reasonable fractures geometry of simultaneous fracturing for engineering applications needs to be investigated.

Table 1
Input parameters for simulation cases.

Input parameters	Value	Units
Young's modulus, E	50	GPa
Poisson's ratio, ν	0.25	
Fluid viscosity, μ	10	$mPa{\cdot}s$
Tensile strength, σ^0_{max}	2	MPa
Formation permeability, k_0	0.1	mD
Fracture height, h_f	80	m
Initial fracture half-length, l	1	m
Initial pore pressure, p_w	40	MPa
Maximum in-situ horizontal stress, σ_{max}	60	MPa
Minimum in-situ horizontal stress, σ_{min}	50	MPa
Porosity, ϕ	0.08	
Perforation diameter, d	10	mm
Perforations number, n	10	
Fluid density, ρ	1800	kg/m^3

In this paper, a numerical model of nonplanar fractures initiation in porous media is established based on XFEM to simulate multiple fractures initiation with simultaneous injection method. The fluid distribution into each fracture is dynamically calculated by combining perforation friction pressure and fluid pressure inside the fractures. Sensitivity studies are conducted to investigate the initiation of simultaneously generated multiple fractures. The strategies to achieve reasonable fractures geometry are presented through injection control of each fracture in horizontal well.

2. Modeling and simulation method

2.1. Fracture initiation model

In this paper, the fracture initiation model is established base on a 2D plane strain assumption. The extended finite element method (XFEM) is utilized to calculate solid deformation and fracture propagation, including the mechanical interaction of multiple fractures. Lubrication equation (Batchelor, 1967) is applied to represent fluid flow inside the fractures. Solid deformation, fluid flow in porous media, fluid flow inside the fractures and the fluid injected into each fracture are fully coupled in this model. The fracture initiation direction is determined by the maximum in-situ stress principle.

2.1.1. Solid deformation

In fluid-filled porous media, the effective stress $\boldsymbol{\sigma}'$ acting on a solid related to the total stress $\boldsymbol{\sigma}$ is expressed as

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' + \alpha p_w \tag{1}$$

where p_w is pore pressure in porous media; α and $\boldsymbol{\sigma}'$ are Biot's number and effective stress, respectively. Equilibrium equation of the porous media can be written as

$$\nabla \cdot \boldsymbol{\sigma} = 0 \tag{2}$$

2.1.2. Fracture initiation and propagation

Fracture initiation and propagation behavior are determined by cohesive traction-separation constitutive law. The traction-separation law assumes linear elastic behavior before the initiation of damage. The elastic behavior is written in terms of an elastic constitutive matrix that relates the nominal stresses to the nominal strains across the interface. Nominal stresses are the force components divided by the original area at each integration point, while nominal strains are the separations divided by the original thickness at each integration point. The damage initiation is the beginning of degradation of the material. The degradation begins as the stresses satisfy specified fracture initiation criteria. The maximum principal stress criterion is used in this model and it is written as

$$\left\{ \frac{\langle \sigma_{max} \rangle}{\sigma^0_{max}} \right\} = 1 \tag{3}$$

where σ_{max} and σ^0_{max} are the maximum principal stress and the maximum allowable principal stress, respectively. The damage evolution is the degrading of material stiffness after the corresponding damage initiation criterion is reached. A scalar damage variable, D, is the averaged overall damage. It is equal to 0 initially. If the damage evolution occurs, D evolves from 0 to 1 monotonically after the initiation of damage. The stress components are expressed by the damage as