Journal of Natural Gas Science and Engineering 29 (2016) 329–336

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Optimal spacing of sequential and simultaneous fracturing in horizontal well

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ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
4 January 2016
Accepted 18 January 2016
Available online 19 January 2016

Keywords:
Unconventional reservoirs
Optimal spacing
Horizontal well
Fracture network
Sequential fracturing
Simultaneous fracturing

ABSTRACT

Sequential and simultaneous fracturing are two main fracturing methods for creating multiple hydraulic fractures in horizontal wells. The fracture spacing of these two fracturing scenarios is critical for creating fracture network to improve unconventional gas or oil reservoirs production. In this paper, a fully coupled (flow and mechanics) hydraulic fracture propagation model based on extended finite element method (XFEM) is established to account for the sequential and simultaneous propagation of nonplanar fractures. By mapping the distribution of in-situ stress contrast during fracturing process, we calculate the fracture network area that is the extent of low in-situ stress contrast zones. The fracture spacing that satisfies the requirement of preventing sand plug as well as creating large field of fracture network is optimal. Sensitivity studies have been conducted for optimal spacing. It is shown that optimal spacing will decrease with in-situ stress contrast, and is not sensitive to varying Young's modulus of the rock matrix. The method presented in this paper can be used in horizontal well design to estimate reasonable fracture spacing.

1. Introduction

Multiple-fracture treatments in horizontal wells are the key technology that depletes unconventional oil or gas reservoirs economically (Pope et al., 2010; Chaudhri, 2012; Yu and Sepehrnoori, 2013). Due to the difficulties of diagnostic techniques for measuring individual fracture and fracture network, numerical simulation remains an important tool for engineers to estimate the geometry of fractures and fracture network. The problem associated with modeling hydraulic fractures has been addressed by many papers in recent years. Wu and Olson (2015) developed a numerical model based on displacement discontinuity method (DDM) to simulate simultaneous multi-fracture treatments for fully coupled fluid flow and fracture mechanics in horizontal wells. The cohesive element method has been applied to modeling viscosity-dominated hydraulic fractures (Zhang et al., 2010; Chen, 2012; Wang et al., 2012, 2015a). Weng et al. (2014) presented a complex fracture network model that simulates hydraulic fracture networks created during the stimulation treatment and proppant placement. Sesetty and Ghassemi (2015) developed displacement discontinuity method for sequential and simultaneous hydraulic fracturing in single and multi-lateral horizontal wells. Wang (2015) proposed a numerical model for nonplanar hydraulic fracture propagation in brittle and ductile rocks using XFEM with cohesive zone method. The mathematical and numerical models for estimating the production of shale gas have been presented (Yu et al., 2014; Zhang et al., 2014, 2015). There are many earlier works focus on creating fracture network. Olson and Taleghani (2009) studied multiple hydraulic fractures growth and their interaction with natural fractures based on displacement discontinuity method. They found that low in-situ stress anisotropy tends to improve fracture complexity in naturally fractured reservoirs. Fu et al. (2013) built an explicitly coupled hydro-geomechanical model for simulating hydraulic fracturing in arbitrary discrete fracture networks. Their simulation results demonstrate that large field of fracture network could be created in low in-

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http://dx.doi.org/10.1016/j.jngse.2016.01.024

situ stress contrast reservoirs. Guo et al. (2015) simulated a hydraulic fracture crossing a cemented natural fracture. The in-situ stress contrast was found to be the key parameter that contains how a hydraulic fracture propagates across a natural fracture. The previous works showed the complex interaction between fractures and suggested that in-situ stress contrast plays a vital role in the creating of fracture network. However, the simulation of fracture network during fracturing process for practical engineering applications is still a challenge work.

The spacing between fractures is critical for the success of multiple fracture treatments of horizontal wells. There are many earlier works focusing on the interaction of fractures and spacing optimization. Roussel and Sharma (2011a) investigated the stress perturbation induced by the propped fracture. Their results demonstrated that a stress reorientation of 90° can occur in the vicinity of a transverse fracture. This zone is called the stress reversal region, and the fracture spacing should be large enough to restrain the propagation of longitudinal fractures. They further investigated multiple-fracture deflection in horizontal well, and proposed that the spacing that makes the main fracture to deflect up to 5° is optimal (Roussel and Sharma, 2011b). Their results provided some new insights on spacing optimization in horizontal well. Morrill and Miskimins (2012) investigated the sensitivity of stress shadow to various reservoir properties and optimized hydraulic fracture spacing in unconventional shales. Soliman et al. (2010) studied the Texas-two step method in horizontal well and presented that fracture spacing is designed to achieve isotropy of in-situ stress and facilitate the reorientation of in-situ stress. Yu et al. (2014) performed a sensitivity study of gas production for a shale gas well with different geometries of multiple transverse hydraulic fractures. They revealed that the outer fractures contribute more to gas production when fracture spacing is small due to the effect of fracture interference. Liu et al. (2015) numerically simulated the connectivity of fracture network produced by Texas-two step method and proposed a new method for fracture spacing optimization in horizontal shale-gas well. The previous works focus on the interaction between fractures with a given fracture length. However, the in-situ stress is changing during the fracture propagation, which in turn affects the propagation and intersection of natural fractures and then the fracture network. The combination of nonplanar fractures propagation and fracture network during fracturing process for spacing optimization of sequential and simultaneous fracturing in horizontal well has not been presented yet.

In the process of fracturing operation, the proppant is injected in conjunction with the fracturing fluid to prevent the closure of fracture surface after releasing the fluid pressure. The proppant is a number of small particles, typically sand, treated sand or man-made ceramic materials, so the fracture width must be large enough to make the proppant injection feasible. Zhou et al. (2014) investigated a low-efficient hydraulic fracturing operation in a tight gas reservoir in the North German Basin. The results demonstrated that the transporting and setting of proppant can result in a different closure of fracture surface. The full closure of a fracture at the perforation will lead to a low productivity. In practical, the fracture width has to be large enough along the propagation path when the proppant is added in the injection fluid, otherwise sand plug will occur and results in serious engineering accident. It is necessary to investigate the mechanical interaction between fractures in horizontal well and then the width of the fractures to avoid the sand plug.

In this paper, a numerical model of nonplanar fractures propagation in porous media was established to optimize fracture spacing in sequentially and simultaneously fractured horizontal well. The mechanical interaction of proppant to fracture surface and the sand plug during fracturing process are incorporated in our modeling and simulation. The fracture network is characterized by low in-situ stress contrast during fracture propagation. Optimal fracture spacing is achieved by calculating the average fracture network width with the varying fracture spacing in our model.

2. Modeling and simulation method

2.1. Fracture propagation model

The fracture propagation model presented in this paper is based on two-dimensional plane strain and couples porous media deformation and fluid flow. The extended finite element method (XFEM) is used to represent the mechanics of fractures and their opening, including the mechanical interaction with closely spaced fractures. Fluid flow in the fractures is determined by lubrication equation. The effect of propped fractures on in-situ stress as well as the propagation of other fractures is taken into account by applying truss model on fracture surfaces. The maximum in-situ compressive stress principle is used to determine the fracture propagation direction.

2.1.1. The cohesive low

The fracture initiation and propagation analysis is governed by cohesive traction-separation constitutive behavior. Linear elastic behavior followed by the initiation and evolution of damage is assumed in the traction-separation model. The elastic behavior is written in terms of an elastic constitutive matrix that relates the nominal stresses to the nominal strains across the interface. The nominal stresses are the force components divided by the original area, while the nominal strains are the separations divided by the original thickness.

Damage initiation is the beginning of degradation of the response of a material. The process of degradation begins when the stresses or strains satisfy certain specified damage initiation criteria. The maximum principal stress criterion is adopted in this paper and it can be written as

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

where, σ^0_{max} represents the maximum allowable principal stress. The symbol $\langle\ \rangle$ represents the Macaulay bracket (i.e., $\langle \sigma_{max} \rangle = 0$ if $\sigma_{max} < 0$ and $\langle \sigma_{max} \rangle = \sigma_{max}$ if $\sigma_{max} \geq 0$). Damage is assumed to initiate when the maximum principal stress ratio (as defined in the expression above) reaches a value of one.

Damage evolution describes the degrading of material stiffness after the corresponding initiation criterion is reached. A scalar damage variable, D, represents the averaged overall damage. It initially has a value of 0. If damage evolution occurs, D monotonically evolves from 0 to 1 after the initiation of damage. The stress components are affected by the damage according to

$$\mathbf{t} = \begin{cases} (1 - D)\bar{\mathbf{t}} & \text{damage initiated} \\ \bar{\mathbf{t}} & \text{no damage occurs} \end{cases} \tag{2}$$

where $\bar{\mathbf{t}}$ are stress components predicted by the linear elastic traction-separation behavior for the current separations without damage. For linear softening, the scalar damage variable, D, is expressed with the following form