Journal of Petroleum Science and Engineering 132 (2015) 86–93

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Optimal spacing of staged fracturing in horizontal shale-gas well

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ARTICLE INFO

Article history:
Received 24 November 2014
Received in revised form
12 May 2015
Accepted 14 May 2015
Available online 22 May 2015

Keywords:
Shale gas
Fracture network
Hydraulic fracturing
Optimal spacing

ABSTRACT

Shale reservoirs have low or ultra-low permeability and porosity, and require achieving economic production rates by creating fracture network. The spacing between fractures is thought to be a major factor in the success of horizontal well completions. The opening of a propped transverse fracture in horizontal wells causes a reorientation of in-situ stresses in its neighborhood, which in turn affects the creation and distribution of stress-relief fractures. In this paper, the extent of stress reorientation has been calculated for fractured horizontal well using two-dimensional numerical model of the stress interference induced by the creation of propped fracture. Staged fracturing in horizontal well is simulated based on an alternate sequencing of transverse fractures. By mapping the angle of stress-relief fractures generated by different fracture stages, we calculate the network area that is the extent of the intersection of stress-relief fractures. Our results demonstrate that the network area has a peak value with the varying fracture spacing and therefore, the associated spacing is optimal fracture spacing. The effect of in-situ stress contrast and net pressure on the optimal fracture spacing has been investigated. It is shown that optimal fracture spacing will increase with lower stress anisotropy or larger net pressure. Finally, the effect of proppant on optimal spacing is investigated. The results presented in this paper can offer some new insights on the completion designs, such as optimizing fracture spacing and improving the conductivity of rock matrix.

1. Introduction

Hydraulic fracturing in shale gas reservoirs has often resulted in complex fracture network growth, due to promoting the propagation and connection of natural fractures, as evidenced by microseismic monitoring (Warpinski et al., 1998; Maxwell et at., 2002; Fisher et al., 2002; Cipolla et al., 2005; Calvez et al., 2007; Daniels et al., 2007). It has been studied extensively by researchers from different aspects. Gale et al. (2007) studied the importance of natural fractures on hydraulic fracture treatments. Zhao et al. (2013) presented new insight into fracture network generation in reopening and slippage of natural fractures. Yu et al. (2014) performed a sensitivity study of gas production for a shale gas well with different geometries of multiple transverse hydraulic fractures. Olson et al. (2009) and Rahman and Rahman (2013) investigated fracture propagation behavior in the presence of natural fractures. Chen (2012) has applied the cohesive element method to modeling viscosity-dominated hydraulic fractures. Significant progress has been made in developing numerical hydraulic fracture models in recent years (Vandamme and Curran, 1989; Zhang and Jeffrey, 2006; Zhang et al., 2007; Adachi et al., 2007; Lecampion and Detournay, 2007; Dean and Schmidt, 2009; Ji et al., 2009; Zhang and Ghassemi, 2011; Wu and Olson, 2013). The propagation of a cohesive crack in porous media was studied based on the extended finite element method (Mohammadnejad and Khoei, 2013a, 2013b). Hamidi and Mortazavi (2014) used distinct element method for simulating the initiation and propagation of three-dimensional hydraulically induced fractures. Weng et al. (2014) presented a complex fracture network model that simulates hydraulic fracture networks created during the stimulation treatment and proppant placement. Ding et al. (2014) investigated hydraulic fractured wells with improved coarse grid techniques for computational efficiency in practically applications. Numerical simulations of main fracturing with fracture propagation, closure, contact and proppant transport were presented by Zhou et al. (2014).

Texas-two step fracture method is an alternate fracturing technique in horizontal well fracturing and has been widely accepted in improving fracture complexity (Soliman et al., 2010). Roussel and Sharma (2011a) have verified that alternate fracturing

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http://dx.doi.org/10.1016/j.petrol.2015.05.011
0920-4105/

tends to create more complex fractures than consecutive fracturing and simultaneous fracturing do. This method has brought focus on the investigation of reasonable fracture spacing for successful well completion. However, a comprehensive model that calculates the optimal fracture spacing has still yet to be established.

Hydraulic fracture growth has been documented surprising complexities in many geological environments (Warpinski et al., 1998; Cipolla et al., 2009). There are a number of mathematical and numerical approaches that can be employed to solve the stress reorientation caused by a propped fracture in a horizontal well, such as analytical solution of stress distribution in the neighborhood of a crack and numerical result of stress changing along the longitudinal direction (Sneddon, 1946; Sneddon and Elliott, 1946; Soliman et al. 2010). Warpinski and Branagan (1989) presented extensive discussions of this subject with the semi-infinite fracture model. Many earlier researches focus on in-situ stress perturbation to fracture extension and fracture spacing optimization (Soliman et al., 2010; Roussel and Sharma, 2011a, 2011b; Morrill and Miskimins, 2012). Roussel and Sharma (2011a) presented that a stress reorientation of 90° can occur in the vicinity of a transverse fracture in a horizontal well. This zone is called the stress reversal region, and the fracture spacing should be large enough to restrain the initiation of longitudinal fractures which might intersect the previous fracture in Texas-two step method (Roussel and Sharma, 2011a). They proposed that the spacing that makes the main fracture to deflect up to 5° is optimal (Roussel and Sharma, 2011b). However, the intersection mechanism of complex fracture network is not included in their model. Soliman et al. (2010) studied the Texas-two step technique and presented that fracture spacing is designed to achieve isotropy of in-situ stress and facilitate the reorientation of in-situ stress, so that the stress-relief fractures caused by different fracturing stages can intersect each other and generate large field of fracture network in rock. However, the complex intersection of stress-relief fractures with random orientations has not been investigated yet.

In horizontal well completion, the opened fracture is filled with proppant after fracturing to avoid the closure of fracture (Khanna et al., 2014). The width of the propped fracture depends on the fracture length and the amount of sand pumped during the fracturing process. Typically, a fracture is only partially filled with proppant due to the plugging of proppant particles between the asperous fracture walls or their sedimentation during the proppant injection stage (Khanna et al., 2014; Ouyang et al., 1997). Partial filling of a hydraulic fracture can lead to a complex residual opening profile and the distribution of stress during the production stage (Neto and Kotousov, 2012, 2013). Nevertheless, no much attention has been given to the residual openings after the hydraulic pressure is released. Different loadings on fracture applied by proppant can also have a high impact on stress reorientation as well as the optimal fracture spacing.

In this paper we address the problems posed above by showing how stress interference can lead to the intersection between stress-relief fractures and then the connectedness of large fracture network in the rock. Optimal multi-transverse fracture spacing is achieved by mapping the fracture network ratio with the varying fracture spacing in our model. The effect of proppant on optimal spacing is also incorporated in our modeling and simulation.

2. Modeling and simulation method

2.1. In-situ stress reorientation caused by single propped fracture

The opening of a propped transverse fracture in horizontal well causes a reorientation of in-situ stress in its neighborhood, which in turn affects the propagation of subsequent main fractures and stress-relief fractures as what is called stress shadowing (Roussel and Sharma, 2011b; Taghichian et al., 2014). Microseismic measurements confirmed the existence of this stress-shadowing effect during horizontal well completions (Fisher et al., 2004; Mayerhofer et al., 2006). There are a number of approaches that can be employed to solve stress interference caused by hydraulic fracturing, such as the analytical model proposed by Sneddon and Elliott (1946). Their model has given the components of stress by single propped fracture as follows:

$$
\begin{aligned}
&\frac{1}{2}\left(\Delta\sigma_x + \Delta\sigma_y\right) = p_{net}\left\{\frac{r}{\sqrt{r_1 r_2}}\cos\left(\theta - \frac{1}{2}\theta_1 - \frac{1}{2}\theta_2\right) - 1\right\}\\
&\frac{1}{2}\left(\Delta\sigma_y - \Delta\sigma_x\right) = p_{net}\frac{r\ \sin(\theta)}{c}\left(\frac{c^2}{r_1 r_2}\right)^{3/2}\sin\frac{3}{2}(\theta_1 + \theta_2)\\
&\Delta\tau_{xy} = p_{net}\frac{r\ \sin(\theta)}{c}\left(\frac{c^2}{r_1 r_2}\right)^{3/2}\cos\frac{3}{2}(\theta_1 + \theta_2)
\end{aligned}
\quad (1)
$$

where c is the half length of fracture, p_{net} is the net pressure in fracture and the other symbols are explained in Fig. 1(a).

This result offers some insight on the magnitude and orientation of stress in the vicinity of an opened fracture. Soliman et al. (2010) proposed the change in three components of the principal stresses resulting from a given net pressure increase after creation of a fracture. Roussel and Sharma (2011a) built a three-dimensional numerical simulation model and studied the effect of fracture aspect as well as Poisson ratio on in-situ stresses.

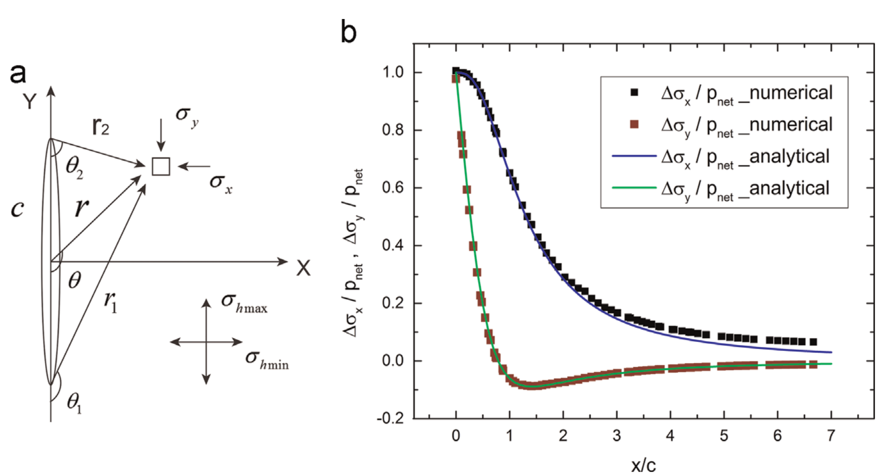

Fig. 1. (a) Schematic representation of a 2D crack parameters in Eq. (1). (b) Comparisons of analytical and numerical stress distributions.