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Stress shadow size and aperture of hydraulic fractures in unconventional shales

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ABSTRACT

Multistage hydraulic fracturing completions together with simultaneous fracturing of parallel laterals are central to enhance productivity of horizontal wells completed in shale reservoirs with extremely low permeability. An efficient fracture network in the reservoir with the least number of deviated or collapsed fractures prevents poor connectivity with the surrounding reservoir volume, reduction in reserve estimates per well, loss in well productivity, reduced drainage areas, and higher completion costs associated with the ineffective fractures. Ignoring the local stress redistribution due to the stress shadow effect may cause fracture deviation or collapse. In this work, a comprehensive numerical study of stress shadow and aperture of three-dimensional hydraulic fractures is presented. Four different scenarios consisting of single or simultaneous hydraulic fractures, contained or not contained, are studied. Key influencing parameters are introduced, different shadow mechanisms are discussed, and a comprehensive set of equations is proposed for stress shadow and aperture prediction of hydraulic fractures. The work presented herein is likely to offer several practical benefits: firstly, it enables improved planning and placement of productive hydraulic fracture treatments; secondly, it offers the potential for considerable cost reductions in completion design and implementation; and thirdly, it allows for an optimal multistage hydraulic fracture treatment that drains larger volumes of the reservoir.

1. Introduction

Unconventional reservoirs have received more attention in recent years because of declining productivity of conventional reservoirs. Specifically, deployment of multilateral drilling technologies together with simultaneous multistage hydraulic fracturing of parallel laterals has been very attractive. In 2009, almost 50% of domestic U.S. gas production was attributed to unconventional resources, and it is estimated to increase to almost 75% by 2035 (EIA, 2011).

However, this growth in the development of unconventional reservoirs, primarily in shale gas, has encountered several challenges. The permeability of these shale reservoirs typically ranges from a few to about one hundred nano-darcies. Consequently, productivity from traditional well architecture and completion schemes has been limited and uneconomical. In early 2000s, several key technological developments enabled the unlocking of this vast resource potential (Andrews et al., 2009).

The issues surrounding connectivity to the productive regions of the reservoir were largely mitigated by developments leading to maturation in horizontal and multilateral well drilling and completion. Of course, the real growth in the gas development occurred as a result of a combination of unconventional well architecture and massive hydraulic fracture treatments, thereby connecting the horizontal laterals to increasingly larger volumes of the reservoir (Warpinski et al., 1997). Eventually, single-stage fracture treatments evolved to multistage stimulation treatments and fracturing of standalone wells progressed to simultaneous fracturing of multilateral wells in order to increase reserves per well, enhance well productivity, and improve project economics (King et al., 2008). Currently, industry is practicing for horizontal drilling orientation along the direction of the minimum horizontal stress. The aim of this practice is to create fractures oriented perpendicular to the axis of the wellbore (Dusseault and McLennan, 2011). This is because transverse hydraulic fractures provide better coverage of the reservoir than longitudinal fractures, and are more efficient in producing gas/oil formations (Soliman et al., 1996). It was proposed that “as the formation permeability gets smaller, it would expectedly take a longer time to deplete the reservoir, and it may be necessary to create more fractures to quickly deplete the reservoir” (Soliman and Boonen, 1997).

Regarding the required number of fractures or the distance between fractures, it is important to notice that the best production should be obtained by an efficient fracture network with the least cost. In the literature, this problem has been investigated from production, and geomechanics perspectives (Roussel and Sharma, 2011; Yu and Sepehrnoori, 2013). In the former method,

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distance between hydraulic fractures is reduced until production does not change noticeably. On the other hand, geomechanical stress change due to fracturing is studied for hydraulic fracture deviation and its collapse on other fractures in the latter approach.

Investigating the distance between hydraulic fractures from the point of view of production, Yu and Sepehrnoori (2013) observed that having fractures too close to each other does not significantly change the production. Based on their results, for a certain set of porosity, permeability, and fracture conductivity, it is possible to economically optimize fracture spacing and length, and the distance between the wells. Of course, that study was done without consideration of geomechanical aspects of the reservoir and the way it influences the determination of optimum spacing between fractures.

Many researchers, however, mentioned that accurate geomechanical information about the rock and its variation through the shale is also important. This is because stresses predominantly control fracture initiation and development (Abousleiman et al., 2007; Barree et al., 2009; Britt and Schoeffler, 2009; Xu et al., 2009).

Fisher et al. (2004) demonstrated that creation of a hydraulic fracture generates a zone of altered local stresses that may impact the orientation of subsequent fractures in a phenomenon known as the stress shadowing effect. Cheng (2009) utilized boundary element method for geomechanical modeling of two-dimensional (2D) hydraulic fractures and indicated that the number and spacing of the fractures need to be carefully selected considering stress change in order to create effective fractures with appropriate geometries. Wong et al. (2013) studied the interaction between adjacent hydraulic fractures using analytical and numerical methods in two dimensions and observed diverging hydraulic fractures outward or even, collapsing of inside fractures on the outside ones as a result of the stress shadow effect. Singh and Miskimins (2010) indicated that an increase in spacing between the fractures induced less interference, and hence requires less breakdown pressure to initiate a fracture.

Stress shadow involves creation of a localized region of high compressive stresses perpendicular to the fracture face in the vicinity of the fracture center. This causes the direction of maximum stress to be reoriented in the region of the stress shadow (Waters et al., 2009). By locating the next treatment in this region, fracture growth is likely to deviate or even occur parallel to the borehole axis and consequently, necessitates optimizing fracture spacing to obtain the maximum number of fractures oriented perpendicular to the wellbore (see Roussel and Sharma, 2011, Morrill and Miskimins, 2012).

In this study, vertical principal stress (S_v) is considered along the z-axis, and the maximum and minimum horizontal principal stresses (S_{Hmax}, S_{hmin}) are on a plane (xoy), perpendicular to the z-axis, respectively, parallel and perpendicular to the hydraulic fracture surface. Application of hydraulic pressure inside the hydraulic fracture changes stresses in horizontal directions and causes horizontal principal stresses to reorient. The change in magnitude and direction of the horizontal principal stresses can be obtained from Eqs. (1a) and (1b), respectively (see Barber, 2010). Deviation angle of principal stresses can also be obtained based on the criteria defined in Eq. (1c).

$$S_{Hmax,},\ S_{hmin} = \frac{\sigma_{xx}+\sigma_{yy}}{2} \pm \sqrt{\left(\frac{\sigma_{xx}+\sigma_{yy}}{2}\right)^2 + \tau_{xy}^2} \tag{1a}$$

$$\tan\ 2\theta_p = \frac{2\tau_{xy}}{|\sigma_{xx}-\sigma_{yy}|} \tag{1b}$$

$$\theta_D = \begin{cases} \theta_p, & \sigma_{xx} > \sigma_{yy} \\ 90-\theta_p, & \sigma_{xx} < \sigma_{yy} \\ 45, & \sigma_{xx} = \sigma_{yy} \end{cases} \tag{1c}$$

in which $\sigma_{xx}, \sigma_{yy}, \tau_{xy}$ are changed stresses in the shadow region after application of the hydraulic pressure, S_{Hmax}, S_{hmin} are changed principal stresses in this region, θ_p is the orientation of principal stresses, and θ_D is the deviation angle of principal stresses.

It is worth mentioning that deviation of maximum principal stress, depending on the magnitude of hydraulic pressure, i.e. the pressure applied inside the hydraulic fracture, can be near the fracture tip or fracture center and it gradually vanishes away from the fracture. Therefore, by defining a threshold angle (θ_T), below which deviations of principal stresses are ignored, the area around the fracture having principal stress deviations larger than this threshold angle can be determined.

Prediction of shadow size around hydraulic fractures has been addressed previously using analytical methods. For example, Jo (2012) proposed a method to predict shadow size based on the analytical stress distribution for plane-strain and penny-shaped fractures (Green and Sneddon, 1950). Eqs. (2a) and (2b) show the proposed equations for predicting shadow size around these two limiting cases of hydraulic fractures.

$$\frac{L_p}{H} = \left\{ \sqrt{\frac{\nu}{2(3-2\nu)}} \quad \text{for plane}-\text{strain fractures(infinite length)} \right. \tag{2a}$$

$$\frac{L_p}{H} = \left\{ \sqrt{\frac{(1+\nu)}{4(5-\nu)}} \ \text{for penny} - \text{shaped fractures(AR} = \text{unity)} \right. \tag{2b}$$

in which L_p is the distance from the center of the hydraulic fracture in the direction perpendicular to the fracture surface to a point where maximum stress contrast is observed, ν is Poisson's ratio, AR is the ratio of height over length of the fracture, and H is the height of the hydraulic fracture. Considering Eq. (1b), it is evident that maximizing the stress contrast means lowering the deviation angle. From Eq. (2a,b), it is seen that the only influencing variables in the shadow size are Poisson's ratio and the fracture height. In addition, Eq. (2a,b) accounts for the aspect ratio, but it only addresses stress shadow size for two limiting cases of plane-strain and penny-shaped fractures. Effects of hydraulic pressure, horizontal stress anisotropy, and aspect ratios of the hydraulic fracture have also been found by other researchers to influence stress shadow size (see e.g., Roussel and Sharma, 2011; Morrill and Miskimins, 2012).

According to the above-mentioned studies in the field of stress shadow, it is realized that most of them have been performed in two dimensions or are more or less descriptive. There is a lack of comprehensive three-dimensional (3D) studies in order to quantify the effect of the most influencing variables on the stress shadow size. As a result, the study of stress shadow for 3D hydraulic fractures is selected in this research work. In addition, aperture of a hydraulic fracture is important in determining proppant type and size. Therefore, the same effort is applied for evaluation of aperture of the fracture as well.

In this paper, effects of different variables on stress shadowing and the aperture of hydraulic fractures in shale plays are studied using a finite-element-based simulator, ABAQUS CAE, 6.12, for the modeling purposes.

The first step is to examine the modeling strategy used in ABAQUS by numerically solving simple fracture geometries for which analytical solutions are available in the literature. Pressurized semi-infinite (Sneddon and Elliot, 1946) and penny-shaped fractures (Sneddon, 1946) are chosen for this purpose. In this step, an appropriately sized model is defined in order to minimize the boundary effects of the model response.

Then, by choosing the appropriate modeling geometry/method, a comprehensive numerical study is designed not only to study the aperture and stress shadow in a descriptive way but also to