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Optimizing Fracture Spacing and Sequencing in Horizontal Well Fracturing

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Abstract

The opening of propped fractures results in the redistribution of local earth stresses. In this paper, the extent of stress reversal and reorientation has been calculated for fractured horizontal wells using a three-dimensional numerical model of the stress interference induced by the creation of one or more propped fractures. The results have been analyzed for their impact on simultaneous and sequential fracturing of horizontal wells.

Horizontal wells with multiple fractures are now commonly used in unconventional (low permeability) gas reservoirs. The spacing between perforations and the number and orienation of transverse fractures all have a major impact on well production.

Our results demonstrate that a transverse fracture initiated from a horizontal well may deviate away from the previous fracture. The effect of the reservoir's mechanical properties on the spatial extent of stress reorientation caused by an opened crack has been quantified. The paper takes into account the presence of layers that bound the pay zone, but which have different mechanical properties from the pay zone. The fracture vertical growth into the bounding layers is also examined.

It is shown that stress interference, or reorientation, increases with the number of fractures created and also depends on the sequence of fracturing. Three fracturing sequences are investigated for a typical field case in the Barnett shale: (a) consecutive fracturing, (b) alternate fracturing and (c) simultaneous fracturing of adjacent wells. The numerical calculation of the fracture spacing required to avoid fracture deviation during propagation, for all three fracturing techniques, demonstrate the potential advantages of alternate fracture sequencing and zipper-fracs to improve the performance of stimulation treatments in horizontal wells.

Introduction

For the past few years, most new wells drilled in the Barnett shale, and other shale plays, have been horizontal wells. Slickwater fracturing is the primary technique used to hydraulically fracture these wells. The horizontal well is generally fractured multiple times, one fracture at a time, starting from the toe. More recently, new stimulation techniques have been investigated to improve the reservoir volume effectively stimulated (Mayerhofer *et al*., 2008). Simultaneous fracturing of two or more parallel adjacent wells, also referred to as simul-fracs or zipper-fracs, aim to generate a more complex fracture network in the reservoir (Mutalik *et al*., 2008; Waters *et al*., 2009).

When placing multiple transverse fractures in shales, it is crucial to minimize the spacing between fractures in order to achieve commercial production rates and an optimum depletion of the reservoir (Cipolla *et al.*, 2009), but the spacing of perforation clusters is limited by the stress perturbation caused by the opening of propped fractures (Soliman *et al.*, 1997). The geometry and width of fractures are strongly influenced by fracture spacing and number, due to mechanical interactions (Cheng, 2009). The center fractures, subject to most stress interference, may exhibit a decrease in their width and conductivity. Stress distributions and fracture mechanics must be well understood and quantified to avoid screen-outs, propagation of longitudinal fractures, or simply deviation from their orthogonal orientation. The presence of natural fractures also impacts fracture propagation increasing fracture path complexity, depending on their preferential orientation and on the importance of the net pressure relative to the horizontal stress contrast. (Olson *et al*., 2009).

Previous studies in the literature on fracture-induced stress interference mostly focus on the effect of a single fracture expected net pressure and the stress contrast: both quantities increase substantially with the number of sequential fractures and a smaller fracture spacing. The stress field in the horizontal plane and the fracture geometries were numerically calculated, based on a displacement discontinuity method for three transverse fractures assuming a homogeneous single-layer formation with the bounding layers not playing any role except to act as barriers to fracture propagation (Cheng, 2009).

Three-Dimensional Model of Stress Interference around a Propped-Open fracture

The results presented here are organized to highlight the important conclusions that we can reach based on the simulations. The validity of numerical simulations is verified through comparison with existing analytical models (Sneddon *et al.*, 1946) for simple fracture geometries. The important addition to existing models consists in the evaluation of the impact of the layers bounding the pay zone on the width of the fracture, which eventually affects the stress interference caused by a propped fracture. The identified dimensionless parameters are the fracture aspect ratio (h_f/L_f), the Poisson's ratio of the pay zone (ν_p), the fracture containment (h_p/h_f), and the ratio of Young's moduli (E_b/E_p). Their effects on the stress contrast generated by the propped-open fracture, and consequently the spatial extent of the stress reversal region, are discussed in the following sections.

Model Formulation

The geometry of the simulated fracture is shown in Figure 1. The model includes the presence of layers bounding the reservoir and cases where the fracture is not fully contained ($h_f>h_p$) are accounted for. The layers bounding the pay zone may have mechanical properties (E_b, ν_b) differing from the pay zone (E_p, ν_p).

The pay zone is homogeneous, isotropic, and purely elastic. Hooke's law relates the components of the strain and stress tensors:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \left(K - \frac{2}{3}G\right)\varepsilon_{kk}\delta_{ij} \tag{1}$$

Where,

$$K = \frac{E}{3(1-2\nu)} \ , \quad G = \frac{E}{2(1+\nu)}$$

A symmetry boundary condition is set up at the fracture center plane, forbidding any deformation in the direction normal to the fracture face. Displacement is allowed along the face of the fracture where a constant pressure, equal to the net pressure p_{net} plus the minimum in-situ horizontal stress S_{hmin}, is imposed. The far-field boundaries are located at a distance from the fracture equal to at least three times the fracture half-length L_f. A zero-displacement boundary condition normal to the "block" faces is applied at outside boundaries. In-situ stresses are initialized prior to the opening of the fracture:

$$\begin{cases} S_{xx} = S_{hmax} \\ S_{yy} = S_{hmin} \\ S_{zz} = S_v \end{cases} \tag{2}$$

Model Validation

Sneddon *et al.* (1946) derived analytical expressions of the additional normal and shear stresses versus the distance normal to the fracture for two geometries: semi-infinite (Figure 2) and penny-shaped fractures (Figure 3).

The results of the three-dimensional numerical model were compared to analytical solutions by plotting the additional stress in the direction parallel (ΔS_{xx}) and perpendicular (ΔS_{yy}) to the fracture as a function of the net extension pressure (p_{net}). The net extension pressure is the stress remaining as the fracture closes on the proppant minus the minimum horizontal stress. In the present study, net pressure is assumed to be constant along the fracture (uniform proppant distribution). Stress distributions are plotted versus the distance normal to the fracture face (y) normalized by the fracture half-height (h_f).

Figures 2 and 3 show that the additional stress in the horizontal plane is always higher in the direction perpendicular to the fracture than parallel to the fracture. As is true initially, the direction of maximum horizontal stress is parallel to the crack, and the stresses are reoriented in the vicinity of the fracture. The numerical results agree well with the analytical solution indicating that the numerical results are correct for this simple case.

The additional stress normal to the fracture (ΔS_{yy}) decreases monotonically with distance away from the fracture. On the

Comparison of Stress Reorientation due to Poroelastic and Mechanical Effects

Stress reorientation around fractured wells can occur due to both the fracture opening and due to poroelastic effects. In the fracturing of horizontal wells, since the production or injection of fluids is minimal, poroelastic effects can be neglected. However, in other cases where significant volumes of fluids have been produced from a well, poroelastic effects can be dominant.

The structure of stress reorientation around a single fracture due to poroelastic effects has been well described in the literature (Siebrits *et al.*, 1998; Roussel *et al.*, 2009). In the vicinity of the fracture, the direction of maximum horizontal stress is rotated 90 degrees from its in-situ direction (for producing wells). Stress reorientation is not just limited to the stress reversal region. The stress distribution resulting from the mechanical opening of a fracture differs from that due to poroelastic stresses. It was shown that outside the stress reversal region, it is the direction of maximum horizontal stress which is oriented perpendicular to the fracture (Figure 4).

The extent of the stress reversal region (L_f') is not limited to 0.58 L_f as is the case for poroelastic effects (Siebrits *et al.*, 1998), but may extend to a distance larger than the fracture half-length (L_f). How far the stress reversal region extends in the reservoir depends mainly on fracture width and height as well as the Young's modulus in the pay zone. The reoriented stress region (outside the stress reversal region) is confined to the vicinity of the fracture, contrary to poroelastic stress reorientation, which can be observed far inside the reservoir.

Effect of Fracture Dimensions

The additional stresses in the parallel and normal directions are plotted versus the dimensionless distance y/h_f normal to the fracture in Figure 5. Both components increase as the fracture length increases compared to its height. The quantity of practical interest, though, is the difference between the additional stress in the direction perpendicular to and in the direction parallel to the fracture (Figure 6). This difference represents the stress contrast that is generated by the opening of the fracture:

$$Generated\ Stress\ Contrast\ (GSC) = \Delta S_{\perp} - \Delta S_{//} = \Delta S_{yy} - \Delta S_{xx} \qquad (3)$$

In most situations the creation of the fracture generates large additional stresses perpendicular to the fracture face. This alters the stress contrast and may cause the direction of maximum stress to rotate 90 degrees in the vicinity of the fracture. The stress contrast generated by the open crack decreases with distance from the fracture (Figure 6). At some distance from the fracture, it becomes smaller than the in-situ stress contrast and the direction of maximum stress is oriented as initially.

The areal extent of the stress reversal region is directly proportional to the fracture height, as the distance to the fracture is normalized by the fracture half-height in our analysis. Figure 6 also shows that as the fracture length increases, the GSC is higher. For instance, assuming the in-situ stress contrast is equal to 0.2 p_{net}, the maximum distance of stress reversal L_f' is increased by 36% for a semi-infinite fracture compared to a penny-shaped fracture.

Effect of Poisson's Ratio in the Pay Zone

The effect of the Poisson's ratio in the pay zone on the stress reorientation around the fracture depends on the fracture geometry. In the limiting case of a penny-shaped fracture ($h_f = L_f$), the GSC is independent of the Poisson's ratio. This can be explained by the fact that the deformation in the horizontal x-y plane is exactly the same as that in the vertical x-z plane. In the more general case where the fracture length differs from the fracture height, Poisson's ratio will play a role.

It is shown in Figure 7 that an opened crack generates more stress contrast in a rock with a low Poisson's ratio. A low Poisson's ratio implies that the deformation in the direction parallel to the fracture is small compared to the deformation along the normal to the fracture. When $\nu_p = 0$, all the deformation occurs along the in-situ direction of minimum horizontal stress ($\varepsilon_{xx} = 0$), thus maximizing the stress contrast generated.

Effect of the Bounding Layers' Mechanical Properties

Models of stress interference available in the literature (Sneddon *et al.*, 1946; Cheng, 2009) assume homogeneous mechanical properties and do not accurately model layered rocks. The rocks bounding gas reservoirs often have different mechanical properties than the reservoir and can play an important role in stress reorientation. Figure 8 shows that the GSC decreases, if the Young's modulus of the bounding layers is higher than in the pay zone. The effect of the bounding layers' Young's modulus was analyzed for a fracture penetration factor h_p/h_f equal to 0.75. The width of an opened crack is proportional to the Young's modulus. The relationship between maximum fracture width w_0 (at the center of the fracture) and net pressure for a semi-infinite fracture is given in Equation 4 (Palmer, 1993). If the fracture penetrates into a weaker

$$w_0 = \frac{4\left(1-\nu^2\right)}{E} p_{net} h_f \tag{4}$$

The effect of the Poisson's ratio in the bounding layers was also analyzed (Figure 10). It is shown that the GSC is independent of this value, and rather depends only on the Poisson's ratio inside the pay zone.

Effect of Fracture Containment

The bounding layers' mechanical properties do not affect the extent of stress reorientation if the fracture is fully contained. In the Barnett Shale, fractures are generally well contained in the pay zone even though "out-of-zone" growth has been measured in the field (Maxwell *et al*., 2002). From the relationship between fracture width and Young's modulus (equation 4), it can be deduced that the further the fracture penetrates into the bounding layers, the more the stress reorientation will be affected by their mechanical properties. For instance, in the case where the Young's modulus is higher in the layers bounding the pay zone, the maximum width of the crack, and consequently the generated stress contrast, decreases as the fracture height increases (Figures 9 and 10).

Application of the Model to Multiple Hydraulic Fractures in Horizontal wells

The quantification of the extent of the stress reversal region around a propped-open fracture is critical in the design of multiple hydraulic fractures in horizontal wells. In low permeability reservoirs such as shales in which the slow depletion allows for short spacing between sequential fractures, great attention should be given to avoid stress interference between transverse fractures. The model of mechanical stress reorientation presented in the previous section of the paper is applied to the case of the Barnett shale. Values of the reservoir and fracture parameters are provided in Table 1. The dimensions of the opened cracks (height, length and width) are similar for all fractures.

Poroelastic effects due to the leak-off of the fracturing fluid into the reservoir are neglected in this study, due to the very low permeability of the shale and the small amount of fluid leak-off during fracturing.

Definition of the Minimum Fracture Spacing

The minimum fracture spacing can be defined as the distance between two adjacent fractures that allows the refracture not to change orientation by 90^o from the original stress field. This is shown as S_{90} in Figure 11. No refracturing should be done within S_{90}. In this stress reversal region, the direction of maximum horizontal stress is parallel to the horizontal well, which would lead the refracture to either grow longitudinal to the well, or screen out as the change in fracture orientation is very rapid. The gain in production and new reserves will be very limited.

Even when refracturing is done past S_{90}, refracture propagation will still be affected by previous fractures. Stress reorientation extends past the stress reversal region, causing a fracture to deviate from its normal trajectory. The fracture spacing needed to limit fracture deviation to less than 5^o is shown as the area outside the S_5 region (Figure 11). The distance from the fracture to the S_5 or S_{10} contours represents the minimum fracture spacing so that the refracture may not be subject to stress reorientation angles higher than 5 and 10^o. Note that the presence of natural fractures, and their effect on fracture propagation, is not modeled. In the situation where the natural fractures are mainly oriented perpendicular to the direction of maximum horizontal stress (as in the Barnett shale), the direction of propagation of hydraulic fractures may significantly deviate from the preferential direction, in particular when stress anisotropy is low (Olson *et al*., 2008).

In very low permeability reservoirs such as the Barnett shale, it is desirable to minimize fracture spacing while at the same time ensuring transverse fracture growth, to efficiently access gas in the reservoir. This implies that the optimal fracture spacing should be just beyond the S_5 contour.

Sequential Fracturing

The stress interference caused by one transverse fracture is shown in Figure 11. Horizontal wells are, however, fractured multiple times. Thus, the values for the minimum fracture spacing provided in Figure 11 are under-estimates (S_{90}=140 ft, S_{10}=320 ft, and S_5=450 ft). The stress perturbation caused by each fracture is cumulative with the effect of all prior fractures. Therefore, stress interference (or reorientation) increases with the number of fractures and also depends on the sequence of fracturing. In this section, we will investigate and compare two fracturing sequences (Figure 12): (a) a conventional consecutive fracturing from toe to heel and (b) sequencing the fractures alternately.

Effect of fracture width and in-situ stress contrast

The values of the fracture width and of the horizontal stress contrast chosen for the base case (Table 1) are respectively 4 mm and 100 psi. As the fracture width increases, the stress contrast generated by the propped-open fracture increases. Thus, depending on the horizontal contrast present in-situ and the fracture design, the stress interference caused by the opening of multiple fractures will be affected. In Figure 13, the distance between the fracture and the isotropic point (minimum fracture spacing S_{90}) is plotted against fracture width for different values of the in-situ stress contrast.

Consecutive fracturing (1-2-3-4-5…)

When a horizontal well is consecutively fractured, the stress perturbation ahead of the latest fracture increases with each additional fracture (Soliman *et al*., 2004) until it reaches a limit, corresponding to the case where the refracture is placed just outside of the stress reversal region (Figure 14). The deviation of the refracture from the stress interference generated by previous fractures is not modeled for simplicity. The calculation of the stress perturbation ahead of the modeled second fracture of Figure 14 provides a good estimate of the minimum distance of refracturing, when taking into account the effect of multiple fractures (Figure 15). The extent of stress reorientation for refracturing are summarized by the values below:

$$\begin{cases} S_{90} = 230 \text{ ft} \\ S_{10} = 430 \text{ ft} \\ S_5 = 600 \text{ ft} \end{cases}$$

In order to limit refracture deviation, the horizontal well corresponding to the values given in Table 1 should be refractured every 430 to 600 ft, which is equal to 1.4 to 2 fracture heights. This calculation corroborates typical values of the recommended fracture spacing found in the literature (Ketter *et al*., 2008).

Alternate fracturing sequence (1-3-2-5-4…)

If the sequence of fracture placement was altered to conduct fractures in the sequence 1-3-2-5-4, it is shown here that the fractures could be placed much closer to each other. This proximity helps to most efficiently drain the reservoir by ensuring that the fractures remain transverse. We recognize that this fracturing sequence may not be possible with current downhole tools and that special tools may need to be developed. However, our goal is to demonstrate the significant benefits of this alternate fracturing sequence compared to the sequential fractures currently being pumped.

The new strategy consists of placing the second fracture at the location of what would traditionally be the third fracture. Perforations for the second fracture are placed at a distance greater than S_5. This ensures that its deviation from a transverse or perpendicular trajectory is minimal. In the first calculation (S = 600 ft, Figure 16), the direction of maximum horizontal stress is reversed along the whole interval separating the fractures. When the fracture spacing is increased to 650 ft, there is an interval where the stress distribution will force the third fracture to grow along a normal path intersecting the horizontal well at the middle point between previous fractures, where the reorientation angle is exactly equal to zero (Figure 17). However, the width of the acceptable interval for the new perforations is extremely narrow (20 ft). For a 700-ft spacing, the width of the refracturing interval is considerably increased (220 ft, Figure 18). If the third fracture were to be initiated in this interval, the stress reorientation would favor transverse fracture growth. The location of this third fracture does not have to be exactly at the mid-point between the previous fractures. In fact, even if the fracture is initiated at some distance from the middle, it will follow a trajectory (as seen in the stress profiles, Figure 18) that will force it to become transverse.

For the last simulation, the fracture spacing is equal to 350 ft (1.17 times the fracture height) which is smaller than the recommended value for consecutive fracturing (S_5=600 ft). The practical advantage of this fracturing sequence, in addition to the fact that minimum fracture spacing is decreased compared to consecutive fracturing, is that stress reorientation is playing to our advantage, forcing the middle fracture to propagate in the optimum direction.

Impact of Adjacent Wells (Zipper-fracs)

The technique of zipper-fracs consists of simultaneously fracturing two parallel horizontal wells. In the particular case that was modeled, the spacing between adjacent wells is equal to the fracture length (Figure 19). It is shown that the extent of stress reversal around each individual fracture is unchanged compared to the case of the single fracture (S_{90}=140 ft). However, the reoriented zone outside the stress reversal region significantly shrank (S_{10}=250<320 ft and S_5=325<450 ft). This is due to the symmetry along the plane x =500 ft (middle plane between adjacent wells), where the reorientation angle is equal to zero.

The worst case scenario for the stress reorientation ahead of the last fracture was calculated for zipper-fracs (second fractures placed at isotropic point), similar to the case described in Figure 14. If stress reversal remain unchanged compared

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