SPE-196966-MS

Conditions of Secondary Fracture Reorientation for Cases of Vertical and Horizontal Wells

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This paper was prepared for presentation at the SPE Russian Petroleum Technology Conference held in Moscow, Russia, 22 – 24 October 2019.

Abstract

An approach to determine stress field near wellbore with existing hydraulic fracture accounting for rising pressure and fluid filtration along the crack has been developed. An estimations of secondary fracture initiation time near wellbore as well as moment of primary crack growth start have been produced. Factual data about mechanical rock properties, stress state and pore fluid pressure was used. It has been shown finally that reorientation of secondary fracture in the case of vertical well is improbable during reinjection. Calculations were made with various magnitude and rate of pumping pressure increasing, value of pore pressure inside formation and main tectonic stress ratio acting at infinity. Similar analysis in the case of horizontal well demonstrated several alternative mechanisms of secondary fracture initiation: simulteniously with existing crack growth new fractures along and orthogonal to well trajectory may appear. Which of type will become dominant depends on actual geomachanical conditions and primary fracture characteristics. Obtained estimations have been compared with field observations.

Introduction

Constantly increasing volumes of refracturing operations show the need to develop effective tools for predicting and analyzing the results of such operation in order to optimize the use of this procedure in field conditions. The use of secondary pumping to increase well production rates has proven itself in every day practice, but the physical reasons for this are still the subject of discussion. The effect can, for example, be achieved by repacking and restoring the conductivity of an existing crack or by introducing new intervals. Much attention recently has been paid to possibility of reorienting a crack formed during the reinjection process into a stimulated interval.

Reorientation in this work is understood as formation and growth of secondary fracture from the wellbore in a direction oprthogonal to primary one. At the same time, new crack initiation conditions are significantly different from the initial stress-strain state of the rock: the already existing fracture with proppant and reservoir pressure distribution will have an influence. Analysis of crack reorientation possibility in such a situation requires an accurate assessment of significant physical effects.

The authors developed a physico-mathematical model of near wellbore zone to determine secondary fracture initiation conditions that takes into account external tectonic stresses, the presence of a primary fracture and heterogeneous distribution of reservoir pressures in the vicinity of the wellbore. Analysis of fracture formation time based on given model in the area of stress concentrators was carried out, which demonstrated the most probable scenarios of rupture development during reinjection on a vertical and horizontal wells. Calculations made with parameters observed during real operations allows us to understand is it possible for fracture to redirect.

Vertical Case

The formation of fractures in rock mass appears in the area of the greatest tensile stresses. In the case of reinjection, the distribution of the latter is significantly affected by an already existing crack and the proppant pack formed during the previous operation. The system "well-fracture" under the action of external loads leads to stresses slightly different from the known analytical solutions for the gap and the round hole in the plate and must be modified accordingly. At the same time, it is also necessary to take into account the distribution of pressure created by the pumping fluid, tectonic stress ratio and the level of reservoir pressure at the moment of the operation.

Two possible situations are considered in this study: the formation of a new fracture at the wellbore during the reinjection process and the initiation of rupture at the tip of an old crack. Estimation of the time of critical conditions occurrence allows us to conclude the most likely results.

Primary crack growth

The fluid entering the well during the injection process penetrates into the primary hydraulic fracture and moves in the direction to the tip. As an example such fracture is shown on figure 1. Increasing pressure leads to the development of a stress state in the vicinity of the last one. The stresse reached its critical value provokes the growth of the existing crack. The problem is to find the time for which this gap will be initiated, taking into account the geometry of the problem, the properties of materials, the initial stress state and the history of pressure in the wellbore. In this case, one of the simplest possible cases is considered: two symmetric straight-line cracks growing from the borehole. Common fracture fracture sizes range from 50 to 200 meters.

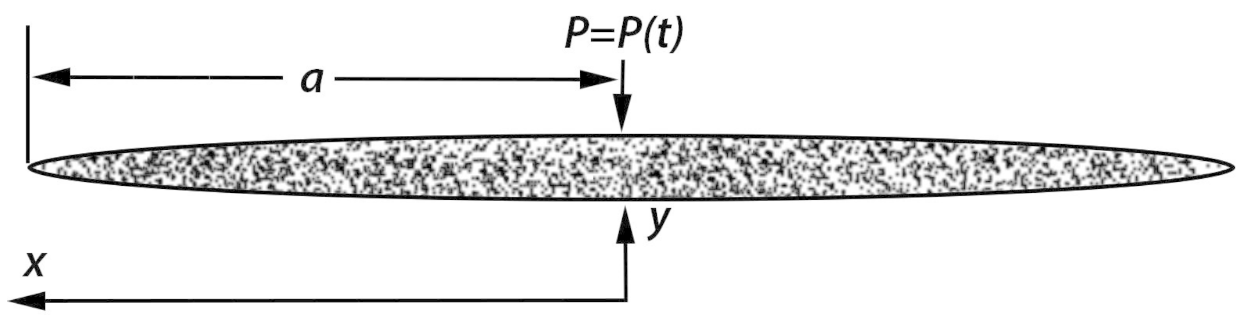

Figure 1—Hydraulic fracture with proppant

The initial problem can be divided in two: determination of the pressure acting on the crack surface and calculating the stress state in the vicinity of the crack tip.

The pressure distribution on the surface of the crack is found by solving the problem of fluid filtration through a proppant pack. Since the crack aperture is much smaller than its other linear dimensions, it is sufficient to consider a one-dimensional problem. Pressure can be found as a solution to the system of equations of continuity, the Darcy and Carter law:

$$\frac{\partial m\rho}{\partial t} + \text{div}\,\rho\vec{u} = -u_L, \quad \vec{u} = -\frac{k}{\mu}\text{grad}\,p, \quad u_L = \frac{C_L}{\sqrt{t - t_{exp}}}. \tag{1}$$

Assuming for simplicity that the density ρ and the porosity m vary insignificantly with pressure, we derive the equation of nonstationary filtration:

$$\frac{\partial p}{\partial t} = \varkappa\frac{\partial^2 p}{\partial x^2} - \frac{\gamma_L}{\sqrt{t}} \tag{2}$$

where ℵ is the coefficient of piezoconductivity, depending on the fluid properties and porous medium, and γ_L characterizes leakage. As the boundary conditions on the wellbore, the pressure function is considered to be known:

$$p(t)\big|_{x=0} = P(t), \tag{3}$$

and at the crack tip zero flow is assumed:

$$u\big|_{x=a,\,x=-a} = 0 \quad \Leftrightarrow \quad (\text{grad}\,p)\big|_{x=a,\,x=-a} = \frac{\partial p}{\partial x}\bigg|_{x=a,\,x=-a} = 0. \tag{4}$$

At the initial moment, the pressure in the system is zero.

In some cases, the described problem can be solved analytically, however, to analyze the re-fracturing procedure, problem was solved numerically using the finite difference Crank-Nicholson scheme.

If the pressure distribution over the crack length is known, then it is possible to determine the magnitude of the stress intensity factor in the vicinity of the crack tip, which comparison with the strength properties of the material gives an answer about fracture appearance. In quasistatic approximation, assuming that the rock behavior near the crack tip is well described by linear fracture mechanics, the stresse state is controlled by the values

$$K_I = \frac{1}{\sqrt{\pi a}}\int_{-a}^{a}(p(x) + n(x))\sqrt{\frac{a+x}{a-x}}\,dx, \quad K_{II} = \frac{1}{\sqrt{\pi a}}\int_{-a}^{a}t(x)\sqrt{\frac{a+x}{a-x}}\,dx, \tag{5}$$

where *p(x)* is the pressure distribution, and *n(x)* and *t(x)* are the normal and tangential components from external tectonic stresses acting on the crack edges. These expressions can also be found numerically. Figure 2 demonstrates pressure dynamics along the crack length and stress intensity factor for the case when the pressure in the wellbore grows linearly with a speed of 62.5 atm / s.

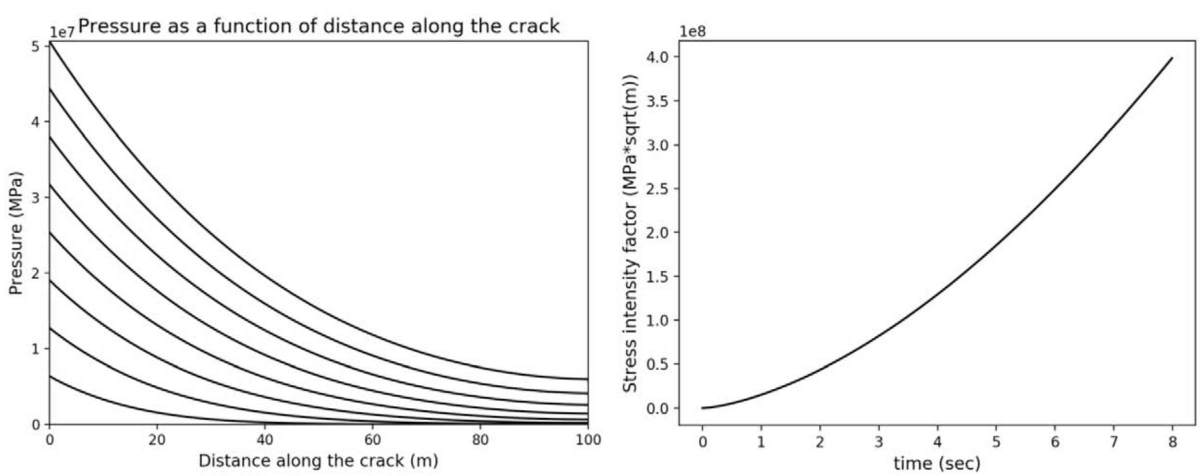

Figure 2—Pressure distribution along the crack (left) and stress intencity factor dynamic (right) for 100 m long fracture.

Initiation at the wellbore

On the other hand, it is necessary to establish whether the fracture can be initiated at the wellbore in a new direction. The study of this issue was conducted numerically using the finite element method. The boundary, as shown on figure 3, of the modeling area consists of several parts: the circular notch corresponding to the well, the existing fracture, adjacent edges and opposite edges. Pressure is applied to the boundary imitating the well and the fracture; due to symmetry, the condition of the corresponding non-displacement is imposed on the adjacent edges, and the stresses corresponding to the external tectonic are set on the remaining part of the boundary.

Figure 3—Stress distribution near pressurized wellbore (left) and pressurized wellbore with fracture (right).

The pressure profiles obtained at the previous stage were used as boundary conditions. It is interesting to note that the presence of a fixed fracture at the wellbore leads to an increase in compressive stresses and thereby prevents the emergence of a new fracture in the orthogonal direction. The infinite increase in pressure in the wellbore leads to tensile stresses in its vicinity (see figure 4), however, under these conditions, the initiation of the growth of a fracture of the primary hydraulic fracturing occurs significantly earlier. Accounting for dynamic effects of inertia does not have a significant influence on the situation.

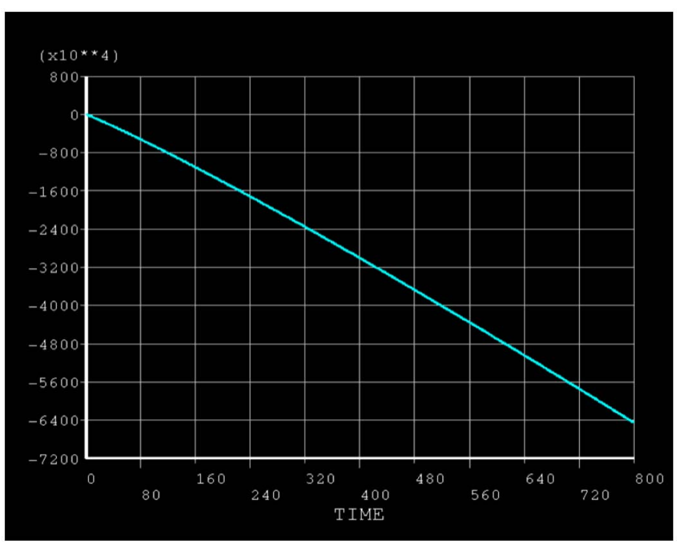

Figure 4—Stress dynamic near potensial vicinity of secondary fracture initiation.

Method described earlier is used to calculate pressure distribution histories along the surface of a primary hydraulic fracture during a secondary pumpings. It is necessary to supplement the developed model with parameters characterizing the rock, the proppant pack with its filtration properties, fracture geometries, and the history of pressure changes in the wellbore. The required data was presented in the table 1:

Table 1—Rock and fracture properties and secondary pumping procedure parameters

Permeability of primary frac, D	100
Leak-off coefficient, cm3/min-1/2	0.03-0.12
Peak pump-in pressure, atm	500-800
Average pump-in pressure, atm	300-500
Time of pressure increasing at start, s	3-8
Primary fracture length, m	50-200
Young modulus, GPa	10-50
Poisson Ratio	0.2-0.3
Density, g/cm3	1.6-2.5
Porosity, %	6-37
Tensile strength (Brazilian test), MPa	0.5-13
S_max, MPa	22-40
S_min, MPa	20-35

For given data, the parameters required to solve the problem of pressure propagation in the fracture during re-injection were determined:

Coefficient of piezoconductivity: 333 m2 / s

Coefficient at the member responsible for leakage: 1.5 * 105Pa * s-1/2

Using these parameters, for different fracture lengths of the primary fracturing (50, 100, and 200 meters), pressure history along the fracture was obtained for times up to 8 seconds after the injection start. Solution for futher times is not considered due to the fact that the fracture initiation (at the tip of the primary hydraulic fracture or new fracture appearance in the vicinity of the wellbore) occurs at the peak pressure time, which for real re-fracturing processes does not exceed 8-10 seconds. The problem has been solved for different loading rates (pressure increase in the wellbore) – from 500 atmospheres in 8 seconds (Figure 3) to 800 atmospheres in 3 seconds (Figure 5).

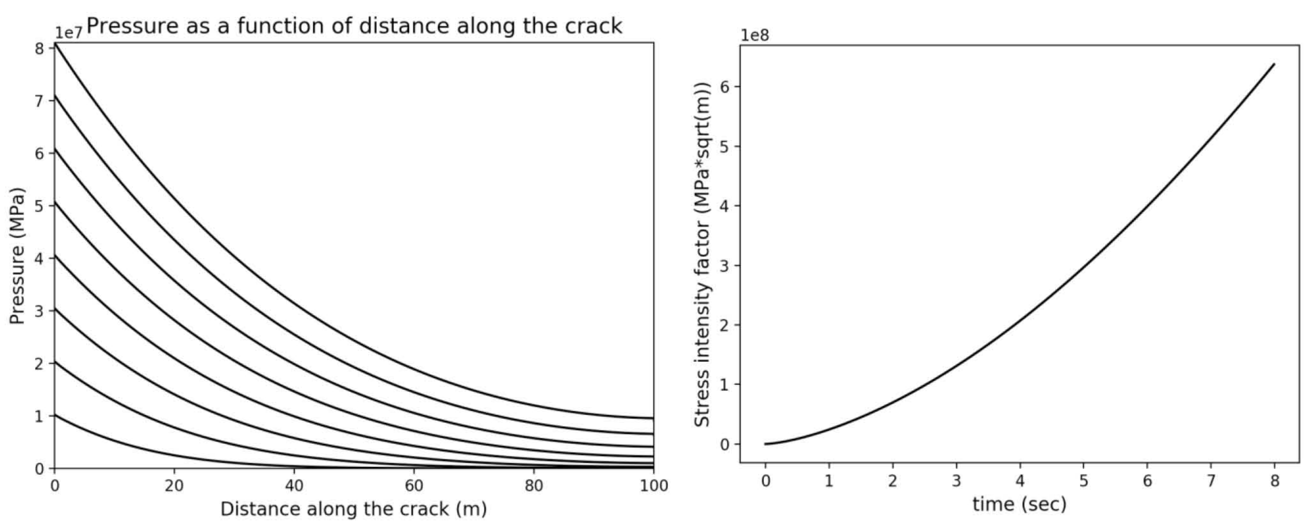

Figure 5—Pressure distribution along the crack (left) and stress intencity factor dynamic (right) for 100 m long fracture with increased pump rate.

Horizontal Well

The results obtained at the previous stage can be used to assess the situation in a horizontal well.

Simulation of secondary hydraulic fracturing on horizontal wells is somewhat different from modeling of secondary hydraulic fracturing on vertical wells. This is mainly due to the fact that the direction of maximum compressive stresses (usually the direction perpendicular to the surface of the earth) lies in the plane passing through the center of the wellbore, and not perpendicular to it. For this case, the transition to a two-dimensional formulation of the problem is somewhat difficult and there is a need to solve the complete problem in a three-dimensional formulation, or to introduce a number of assumptions to some extent limiting the range of tasks to be solved. Among such assumptions:

1. The properties of the rock material surrounding the well are homogeneous and isotropic.
2. Vertical stresses exceed horizontal, so the direction of propagation of destruction always coincides with the vertical.
3. There is a significant difference in the values of the smallest and largest of the horizontal stresses, so the destruction occurs only in one plane – perpendicular to the direction of the smallest of the horizontal stresses (see figure 6).
4. Destruction spreads vertically throughout the thickness of the oil-bearing formation.
5. The magnitude of leaks is constant over the entire area of the existing damage.
6. Leak at any point is a one-dimensional flow normal to the boundary of the existing damage.
7. Download speed is constant.
8. Additional requirements that simplify the model of the spread of hydraulic fracturing in the cavity of the existing damage.

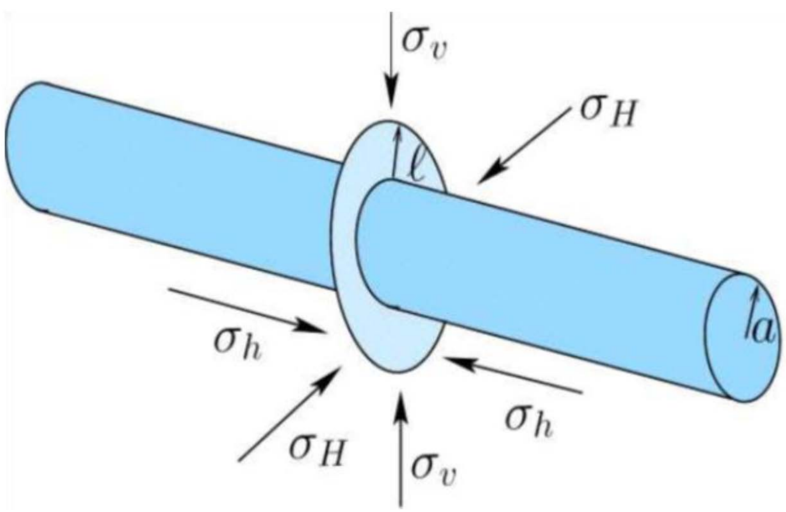

Figure 6—Horizontal well with orthogonal fracture under stresses.

In the case when the assumptions allowed to consider the simplified two-dimensional formulation of the problem are too strong, it is necessary to solve the problem in a full three-dimensional formulation, which can be done by finite element method using, similarly to the model presented in the previous sections. However, such a formulation will be associated with a number of complexities and significant computational power and calculation time, which make it difficult to use this approach to simulate re-fracturing on real wells to predict optimal process characteristics.

The studying problem for the horizontal case can be divided into three subtasks: estimating the growth of an old fracture, initiating a new fracture along the borehole, and initiating a new transversal hydraulic fracture. The first of them was already solved at the previous stage. The second one allows an analytic solution based on the Kirsch equations. Results demonstrated on figure 7.

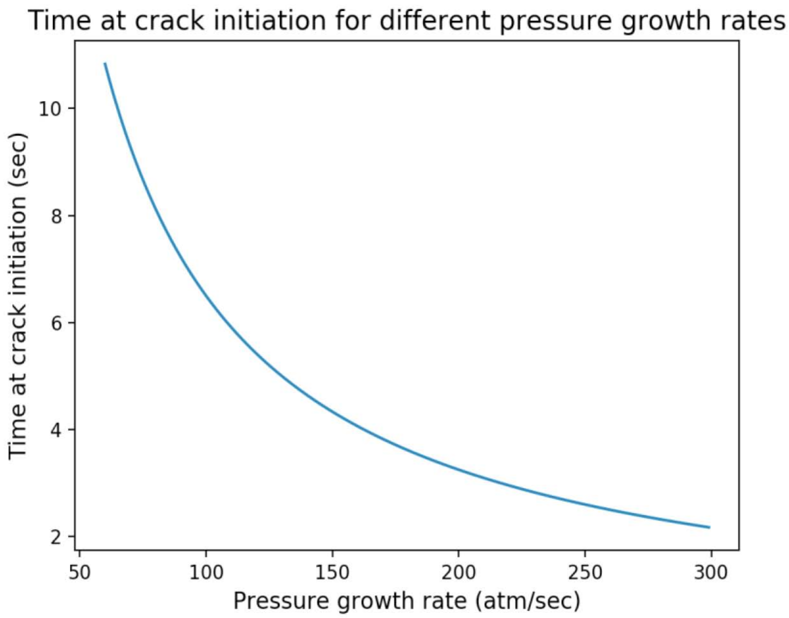

Figure 7—Fracture initiation moment dependance on pressure growth rate.

Third subtusk is initiating a fracture transversal to the wellbore. For simplicity, the symmetric case is considered inside a homogeneous medium, because of it the crack has a round shape. The fluid pressure is not attached over the entire area of the last one, but only in the ring, respectively, of the wellbore. In this case, the asymptotics of the stresses at the crack tip is determined by the following expression:

$$K_I = \frac{2p}{\sqrt{\pi a}}\sqrt{a^2 - b^2} \tag{6}$$

The calculation based on the parameters characteristic of field situations allows to determine the characteristic time of formation of a new hydraulic fracture (see figure 8).

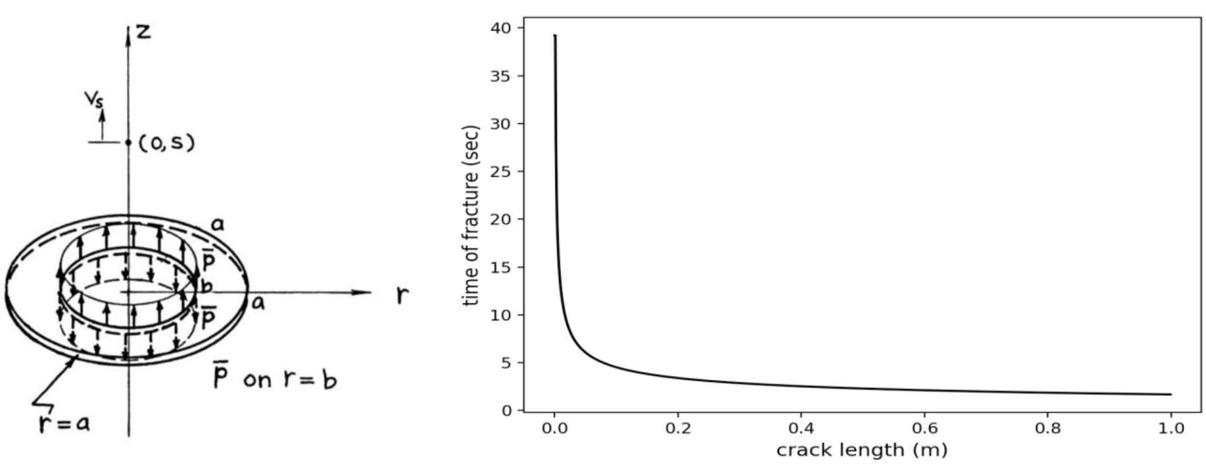

Figure 8—Secondary appeared crack (left) and corresponding time of development dependence on its initial length.

In contrast to the vertical well, the characteristic time for the formation of a new crack in the process of re-injection turns out to be comparable with the initiation of the growth of an old crack for both the longitudinal and transverse cases.

Field Data

Field data observations of fracture reorientation is always a subject of discussion. The limited information and the impossibility of carrying out direct measurements do not allow us to finish the question of this phenomenon and the approaches to its correct modeling.

As an example of the study of this issue we describe the following case. The development of one of the Gazprom Neft fields was organized on the basis of line-drive production system, as shown on figure 9. Both production and injection wells were treated by hydraulic fracturing. Long work in such conditions leads to an inhomogeneous distribution of reservoir pressure and, consequently, a change in the stresses acting into reservoir. Because of this, the risk of fracture reorientation increases with secondary injections and subsequent water breakthroughs into production wells.

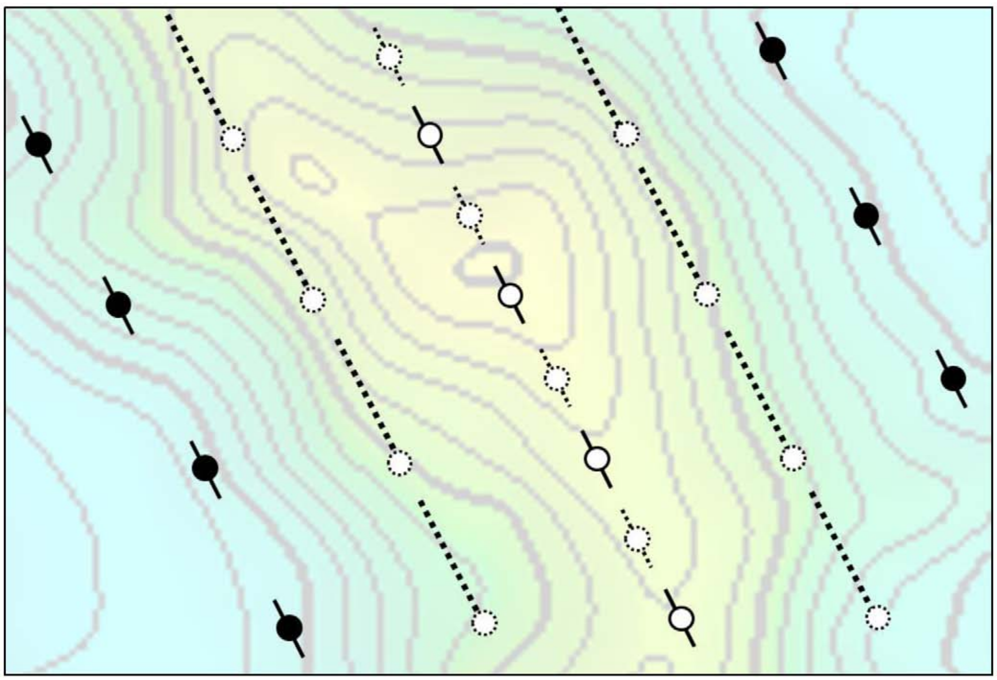

Figure 9—Line-drive production system and infill drilling wells (dotted).

Observations on the parameters of the reservoir pressure maintenance system and production did not allow us to identify increases in risk of breakthroughs with rising in the volume of refracturing operations.

Further, it was decided to make infill drilling to increase production at the field. In the rows of production wells, vertical wells were additionally drilled between the already existed, which were subsequently treated using hydraulic fracturing technology. In addition, between the rows of injection and production wells, horizontal production wells were conducted. Such actions can lead to premature drowning of objects, especially in the case of underestimation of the reorientation phenomenon. However, deviations from the intended behavior were not observed.

An example of this field makes it possible to conclude that the ratio between the existing tectonic stresses, which in the present situation turned out to be so large that the complex pattern of pore pressure distribution did not have a significant effect on the cracks behavior, plays a significant role in fracture re-orientation in a field.

Conclusions

The results of made investigation include following:

- Semianalytical approach to the problem of damage initiation during secondary pumping procedure have been developed. Corresponding program for numerical calculations in both cases of vertical and horizontal well have been realized. This module allows to determine 2D stress field acting inside rock near wellbore with fracture and compute the time of damage appearance in such complex structure.
- Developed physical model takes into account geometrical and filtration properties of primary fracture, reological characteristics of injection fluid and its loss in porous media, acting insitu stresses.
- Estimates of growth start time of primary fracture based on stress intensity factor calculations account for united geometry of circular well and existing fracture, pressure wave propagation through proppant during pumping procedure, fluid losses and static tectonic stress field and even dynamic stress wave movement inside rock medium. They have shown that for parameters close to real primary crack begins to grow through 1-10 seconds after pumping start.
- Estimates of new fracture initiation near wellbore based on maximum tensile damage criteria accounts for united geometry of circular well and existing fracture, aperture of last one, insitu tectonic stresses and pore pressure. For vertical and horizontal cases results significantly differ.
- Analysis of conditions typical for vertical wells and obtained estimations demonstrates that reorientation of new fracture during secondary pumping procedure is improbable and this action leads to development of primary crack.
- Analysis of conditions typical for horizontal wells and obtained estimations demonstrates two alternative mechanisms of new fracture initiation, that may concure with primary crack. Which one will become dominant depence on actual situation.

Developed approach already allows to get correct results and may be generalized to reach better accuracy.

References

1. Sherif Foda, Refracturing: Technology and Reservoir Understanding are Giving New Life to Depleted Unconventional Assets, *JPT*, July 2015, Volume: **67**, Issue: 7
2. Why Re-Fracturing Works and Under What Conditions / H.I. Asala, M. Ah-madi, A. Dahi Taleghani et al. // *SPE Annual Technical Conference and Ex-hibition* / Society of Petroleum Engineers. — 2016.
3. Zhang G.Q., Chen M. Dynamic fracture propagation in hydraulic re- fracturing // *Journal of Petroleum Science and Engineering*. — 2010. — Vol. **70**, no. 3. — P. 266–272.
4. Bratov, V. (2018). Numerical Models for Hydraulic Refracturing on Vertical Oil Wells. *International Journal of Engineering & Technology*, **7**(4.26), 279–284. doi:http://dx.doi.org/10.14419/ijet.v7i4.26.27937
5. J. Adachi, E. Siebrits, A. Peirce, J. Desroches, Computer simulation of hydraulic fractures, *International Journal of Rock Mechanics & Mining Sciences* **44** (2007) 739–-757
6. J. I. Adachi and E. Detournay, Self-similar solution of a plane-strain fracture driven by a power-law fluid, *Int. J. Numer. Anal. Meth. Geomech* **26** (2002) 579-–604.
7. Detournay EE, Cheng AD, McLennan JD. A Poroelastic PKN Hydraulic Fracture Model Based on an Explicit Moving Mesh Algorithm. *ASME. J. Energy Resour. Technol.* 1990;**112**(4):224–230.

8. E. Carter, *Optimum fluid characteristics for fracture extension, in Drilling & Production Practices*, G. Howard and C. Fast, eds., American Petroleum Institute, Tulsa, OK, 1957, pp. 261–270.
9. M.P. Cleary, M. Kavvadas, K.Y. Lam, Development of a fully three-dimensional simulator for analysis and design of hydraulic fracturing, in: *SPE/ DOE Low Permeability Gas Reservoirs Symposium*, Society of Petroleum Engineers of AIME, Denver, Colorado, 1983. Copyright 1983.
10. Lam, K.Y. and Cleary, M.P. Slippage and re-initiation of (hydraulic) fractures at frictional interfaces. *International Journal for Numerical and Analytical Methods in Geomechanics*. 589–604, 1984, T. 8.