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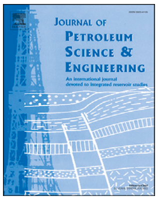

An analytical model for fracture initiation from radial lateral borehole

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A B S T R A C T

Radial drilling-fracturing, the integration of radial drilling and hydraulic fracturing, is an innovative approach to develop low permeability, thin target layer and naturally fractured reservoirs, etc. Understanding the fracture initiation process is required in the practical application to avoid high fracture initiation pressure (FIP) and complex fracture geometries near the wellbore. In this paper, we develop an analytical model to determine FIP, location of rock failure zones and initial fracture direction from the radial lateral borehole. This model is based on the stress superposition induced by cased main wellbore and radial borehole, and the maximum tensile stress criterion is adopted. Then, we perform a series of sensitivity analysis by examining different effects of *in-situ* stress regime, lateral orientation (the included angle between borehole axis and maximum horizontal *in-situ* stress), lateral length, and lateral diameter. Besides, the effect of pre-existing weakness plane, across which the tensile strength is much lower than that of the intact rock, is also investigated, when the plane is drilled through by the radial borehole. Results show that for intact rock with no weakness plane, the *in-situ* stress regime and lateral orientation are main factors influencing FIP, location of rock failure zones, and initial fracture direction. Under the *in-situ* stress regime of normal fault, fracture initiates vertically, and FIP enlarges as lateral orientation increasing; under the *in-situ* stress regime of strike slip, fracture initiates vertically with small lateral orientation, while fracture initiates horizontally with large lateral orientation; and under the *in-situ* stress regime of reverse fault, fracture initiates horizontally with any lateral orientation, and FIP decreases as the lateral orientation increasing. It is also found that when the fracture initiates vertically, the location of rock failure zones is at the base of radial borehole on its top and bottom sides; and when the fracture initiates horizontally, the location of rock failure zone is at the remote region of radial borehole on its right and left sides. The lateral length has a minor effect on fracture initiation, and the influence of lateral diameter is negligible. When the weakness plane is drilled through by the radial borehole, fracture initiation pressure from weakness plane is affected by its occurrence, i.e., azimuth and inclination. FIP is determined by taking the minimum between fracture initiation pressure from rock matrix and the weakness plane. The key findings of this work could provide critical insights into understanding radial drilling-fracturing initiation characteristics.

1. Introduction

Radial drilling is a technology that is able to make a right turn in a cased wellbore (vertical, slanted, or horizontal well) and then penetrate some distance out into the formation (Balch et al., 2016; Dickinson and Dickinson, 1985; Dickinson et al., 1993). The drilling tools can be high-pressure water jet, called radial-jet-drilling (RJD) (Wang et al., 2016), as well as mechanical drill bit (Balch et al., 2016). The formed radial laterals, with radius of 20–50 mm and length of 10–100 m, distributing in one layer or multiple layers, can penetrate the near well damage zone, enlarge wellbore-reservoir contact area (Cinelli and Kamel, 2013; Ragab, 2013), intersect high permeable faults, joints and micro-cracks, and increase productivity with low cost.

However, the diameter of radial borehole is usually very small (less than 50 mm), so drilling alone cannot increase production effectively in formations where there is limited vertical conductivity, very low permeability or natural fractures of limited extent (El-Rabaa and Olson, 1996). Considering that hydraulic fracturing increase production from unconventional reservoirs significantly (Guo et al., 2017a; Yuan et al., 2015b; Yuan et al., 2017), radial drilling-fracturing is innovatively proposed by integrating radial drilling and hydraulic fracturing (Guo et al., 2016, 2017b). As illustrated in Fig. 1, 8 radial laterals, distributing in two

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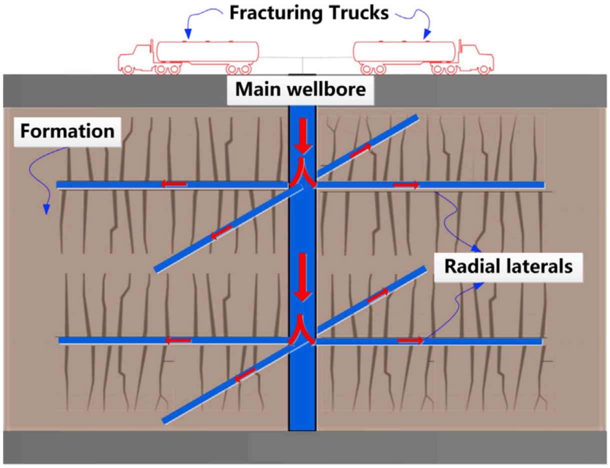

Fig. 1. Schematic diagram of radial drilling with hydraulic fracturing.

layers, are drilled from the main vertical well, and then hydraulic fracturing are operated with various fractures initiating and propagating from these radial boreholes. There have been several practical application in low permeability (Li et al., 2000), aged (Cinelli and Kamel, 2013) and coalbed methane reservoir (Megorden et al., 2013), etc., with good stimulation effect.

When radial drilling-fracturing is conducted, the main role of radial borehole is to provide guidance for the hydraulic fracture. Abass et al. (2009) experimentally proved that vertical radial drilling by waterjet from an open hole horizontal well can precisely guide fracture initiating transversely along the radial hole and propagating in the direction of maximum horizontal stress regardless of orientation of horizontal well. Fu et al. (2015) numerically and experimentally investigated radial drilling-fracturing on coalbed methane formation, and results showed that hydraulic fracture is guided to propagate along the radial lateral orientation, and connects multiple natural fractures. Guo et al. (2016) numerically proved that drilling a branch or multi-branch boreholes parallel to a desired fracture direction is proved to be an efficient way to overcome the influence of original *in-situ* stress field, and guide the fracture in a direction parallel to the direction of the wellbore toward the target area.

Accurate prediction of fracture initiation pressure (FIP), location of initial pressure and initial fracture direction is essential for the successful operation of hydraulic fracturing. Unsuitable design will induce high FIP and complex fracture geometries near wellbore (Van Ketterij and De Pater, 1999; Zhi and Ahmad, 2016; Ghassemi et al., 2016), which will reduce fracture conductivity near wellbore and is harmful to production increase (Rui et al., 2017; Sun et al., 2016a; Yuan et al., 2015a). Numerous studies on fracturing initiation were analytically, numerically and experimentally conducted. Murphy and Fehler (1986) discovered that shear slippage along pre-existing joints is more easily induced than tensile failure by experiments and numerical simulation. El Rabaa (1989) experimentally showed fracture geometry near the horizontal well is controlled by well deviation as well as length of perforation interval, and short perforation interval is recommended to eliminate problems such as multiple fractures, nonplanar fractures with rough wall, etc. Papanastasiou and Zervos (1998) numerically showed that perforation orientations greatly influence fracture initiation pressure as well as location, and the propagation of a major fracture will suppress the propagation of multiple fractures. Hossain et al. (2000) developed an analytical model for initiation of longitudinal, transverse and complex multiple fractures from vertical and horizontal wellbores with and without perforations. Alekseenko et al. (2012) developed a 3D numerical model of fracture initiation form a perforated wellbore based on boundary-element method, predicting the fracture-initiation pressure location and direction of an initial rupture. Abbas et al. (2013) analyzed the completion between transverse and axial hydraulic fractures in open hole horizontal wells based on linear elastic fracture mechanics, and found that the key parameters are the initial defect length and the *in-situ* stress filed. Waters and Weng (2016) established a near-wellbore fracture initiation calculator, proving that fracture initiation, location and orientation is strongly influenced by preformation diameter, eccentricity and orientation, stress regime and well orientation.

Currently, there are few works investigating fracture initiation from radial borehole. Gong et al. (2016) numerically found that under the *in-situ* stress regime of strike-slip fault, radial lateral azimuth, length and diameter are three main factors influencing fracture initiation pressure and starting point. But this work does not consider fracture initiation under stress regimes of normal and reverse fault. Besides, this work cannot predict direction of initial rupture. Hence a comprehensive model for radial drilling-fracturing initiation is still lacking in petroleum engineering.

In this paper, we develop an analytical model for determining fracture initiation pressure (FIP), location of rock failure zones and initial fracture direction in radial lateral borehole. We performed a series of sensitivity analysis by examining different effects including *in-situ* stress regime, lateral orientation, lateral length, and lateral diameter. Besides, the effect of pre-existing weakness plane, across which the tensile strength is much lower than that of intact rock, is also investigated, when the plane is drilled through by the radial borehole.

2. Model development

In this part, we get stress at radial borehole wall by stress superposition induced by main wellbore and radial borehole. Then, FIP, location of rock failure zones and initial fracture direction in radial lateral borehole are determined based on the maximum tensile stress criterion, i.e., fracture initiates at the location where the local maximal tensile stress exceeds the rock tensile strength.

2.1. Assumptions

(1) In radial drilling, the curvature alteration from vertical to horizontal turns in 0.3 m (Marbun et al., 2011). Therefore, radial borehole is regarded as orthogonal intersection with the main wellbore.
(2) We assume that the formation material is homogeneous and linearly elastic, and to have isotropic strength properties, which is suitable for simplified calculations and widely used for analysis of fracture initiation from wellbore and perforations (Alekseenko et al., 2012; Hossain et al., 2000).
(3) The Young's modulus of the cement ring and formation is in the same order of magnitude, while the Young's modulus of the casing is of the order of magnitude higher. To simplify the problem, it is assumed that the Young's modulus of formation and the cement ring is the same.
(4) Before fracture initiating, the fracturing fluid in the radial borehole is almost in the static state (Gong et al., 2016). Therefore, the frictional resistance of fracturing fluid in radial borehole is not considered. However, the friction loss should be considered when it is used in the field (Liu and Ehlig-Economides, 2016, 2017; Massaras et al., 2007).

2.2. Stresses around cased main vertical wellbore

It is recognized that tensile stress is negative, and pressure stress is positive. All stresses in this article are considered as total stresses in distinction with effective stresses. A rectangular coordinate system (*X, Y, Z*) is established such that the origin is at the center of the wellbore cross-section and the *Z* axis is aligned with the wellbore axis. The *X* axis is aligned with the maximum horizontal stress, σ_H, while the *Y* axis is aligned with the minimum horizontal stress, σ_h (Fig. 2). Therefore, the far