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Improving fracture initiation predictions of a horizontal wellbore in laminated anisotropy shales

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ABSTRACT

Increasingly prominent unconventional petroleum resources tend to occur in formations with laminated heterogeneity. The predominant laminated heterogeneity in tight gas shale reservoirs results in considerable variability in the elastic properties along the orientations parallel and perpendicular to the bedding direction.

By incorporating the anisotropic elastic deformation and pore hydro-mechanical coupling effects, a 3D numerical model of fracture initiation from a perforated horizontal wellbore is established. A sensitivity analysis is proposed to evaluate the effects of the anisotropic mechanical behavior and in situ stress conditions on the fracture initiation pressure (FIP) and location of an initial rupture. Comprehensive analysis results revealed elastic anisotropy results in the complex near-wellbore stress concentrations, proved by the fact that the near wellbore fracture tortuosity increases as the perforation azimuth increases, which is not observed in traditional isotropic rocks. Furthermore, perforation parameters including perforation density, perforation diameter, and perforation depth, are also analyzed assuming elastic anisotropy conditions. In addition, a stronger Young's modulus anisotropy causes lower fracture initiation pressure and lower fracture tortuosity at the wellbore face, while the impact of the Poisson's ratio anisotropy is relatively small. Changes in the in situ stress conditions have a significant effect on the fracture initiation pressure whether the rock is an isotropic or anisotropic formation. Numerical simulation results indicate that near-wellbore modeling in horizontal completions in an anisotropic shale is a necessary step for predicting and controlling the potential problems during fracturing treatment and avoiding erroneous completion decisions based on traditional isotropic models.

1. Introduction

An emerging fossil fuel known as “shale gas” is widely used for power generation throughout the world. The proportion of gas from shale reservoirs from exploiting unconventional resources has become significant (Harper, 2008). Hydraulic fracturing is the effective methodology for economically developing tight shale gas with non-Darcy permeability. The procedure of creating several perforation clusters within a selected horizontal well interval is required for the successful design and implementation of a multistage hydraulic fracturing stimulation treatment to gain a higher contact area with the reservoir (King, 2010; Matthews et al., 2007). Clearly, it is essential to have a better understanding of the fracture initiation process to predict and control the variability of fracture initiation pressure between perforation clusters.

Perforation, which is composed of only the fluid channel that has a “good communication” between the reservoir zone and the wellbore, can cause the main hydraulic fracture and natural fractures to communicate better to form a mutual crisscross reticular cracks formation (Soliman et al., 2008). Artificial hydraulic fracturing in petroleum engineering often means the phenomenon of fracture initiation when the pore pressure in the perforation tunnels builds up and reaches a critical point where the maximum principal stress at the borehole becomes a tensile stress, which fractures the rock (Jaeger et al., 2007). A fracture initiated from a wellbore will encounter a complex stress state within the rock that leads to the development of a complex geometry of the propagated

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fracture. A few papers related to the modeling of the fracture initiation process have been published (Yuan et al., 1995; Papanastasiou and Zervos, 1998; Hossain et al., 2000; Zhang et al., 2010), where the formation initiation pressure of an open hole completion and casing perforation completion and the angle between the axis of perforation and the crack fracture direction, respectively, for the vertical and horizontal well were derived. An earlier study demonstrated that the main perforation parameters (e.g., length, diameter and orientation) can predict and control the variability of the fracture initiation pressure (FIP) during multistage fracturing treatment (Alekseenko et al., 2012). Based on their research, Daneshy and Fallahzadeh maintain that hydraulic fracture may initiate at different positions within the same perforation tunnel or at the wellbore-perforation interface and possibly not from the surface of perforation tunnel (Daneshy, 1973; Fallahzadeh et al., 2010). For horizontal wellbores, a unanimous conclusion was reported that fracture initiation pressure is minimal for perforations that are aligned with the direction of maximum stress and higher for misaligned perforations (Berhmann and Elbel, 1991; Waters et al., 2006). Moreover, a considerable number of physical modeling experiments have been conducted to optimize the perforation parameters of horizontal wells to determine the fracture initiation pressure, geometry and the law of fracture initiation and propagation (Kim and Abass, 1991; Abass et al., 1996; Rabaa, 1998; Ketterij et al., 1997). Many studies on the fracture initiation mechanism have been performed by domestic and overseas scholars. However, the simulation of fracture initiation for hydraulic fracturing in reservoir engineering is still a very challenging process because of the complexity of the stress distribution around the well caused by factors such as geomechanical properties, discontinuity characteristics of the formation, fracturing fluid penetration effect, pore pressure, etc.

Importantly, the exploitation of unconventional oil and gas resources tends to occur in formations with elastic anisotropy. In fact, shale is the best representation of elastic anisotropy among various laminated sedimentary rock systems with different levels of texture. The laminated heterogeneity of shale results in high variability in the elastic mechanical properties along orientations perpendicular and parallel to the bedding, with a difference varying from 100% to 400% (R. Gautam, 2004). Because of the significant anisotropic deformation and strength characteristics, the failure condition and stability of laminated shale are more complex compared to those of isotropic rock masses (Athavale and Miskimins, 2008; Pariseau, 1968; Fjaer et al., 2008). Previous researchers have claimed that the conventional method for stress analysis that assumes the rock has homogeneous isotropy to simplify the mathematical complexities can cause inaccuracies and often underestimates/overestimates fracturing pressure during fracturing treatment (Aadnoy et al., 1987; Aadnoy, 1988; Zoback, 2007; Prioul et al., 2011). Most of them neglected the effect of the differences in the rock mechanical parameters in the vertical and horizontal directions. To consider the sensitivity effects of anisotropy on fracture initiation, some scholars have proposed analytical solutions to study the stress distribution around a wellbore drilled horizontally in a transversely isotropic formation (Suárez-Rivera et al., 2006; Amadei et al., 1987; Ong and Rogeries, 1993; Lekhnitskii, 1963; Jaeger et al., 2007; Abousleiman and Cui, 1998). Obviously, the conditions of the analytical solution applicable in these studies are applicable for the wellbore only and not for the perforation cavity. Due to the complexity of the problem, this approach has limited applicability for stress determination of the perforation. Only a few papers are available that describe modeling of the fracture initiation process and that explored the complicated geometrical configuration of a perforated wellbore (Weijers and de Pater, 1994; Serajian and Ghassemi, 2011; Suárez-Rivera et al., 2009). Detailed numerical modeling is thus needed to better understand the fracture initiation mechanisms that control the fracture initiation process to improve completion strategies and stimulation designs.

In our research, we propose a new numerical simulation model that considers the perforation parameters for predicting variations in the fracture initiation pressure in laminated shale formations. There are three main improvements compared with previous research: (1) the simulation considers the anisotropic elastic deformation and pore hydro-mechanical coupling effects together; (2) the birth and death element method is adopted in the excavation step to kill the wellbore and perforation tunnel elements to simulate the drilling and perforating processes; and (3) sensitivity analysis is presented to provide insights into the effects of changing the degree of elastic anisotropy and in situ stress ratios on the fracture initiation pressure in laminated shale formations.

2. Theory description

2.1. The basic theories of the seepage-deformation coupling method

Rocks have been treated as a poroelastic and permeable medium consisting of two components: a solid and a fluid part. Therefore, the void space, which plays an important role in rock mechanical seepage behavior, will be included. The solutions of seepage-deformation coupling can be divided into sequential coupling and direct coupling. Sequential coupling is the method that uses cross iteration of the seepage and stress field but has no actual coupling. The direct coupling method uses the seepage-deformation coupling element, including all the degrees of freedom of the placement and pore pressure, and it achieves whole coupling during the analysis, which is superior to sequential coupling.

We now proceed to establish a fracturing model based on a three-dimensional consolidation equation proposed by Biot for coupled deformations and fluid flow in the permeability field (Biot, 1941), which is often called "true three-dimensional consolidation theories". The Biot consolidation equation can be expressed by the displacement and pore pressure as follows:

$$\begin{cases} -G\nabla^2 u^s - \dfrac{G}{1-2\nu}\dfrac{\partial}{\partial x}\left(\dfrac{\partial u^s}{\partial x}+\dfrac{\partial \nu^s}{\partial y}+\dfrac{\partial w^s}{\partial z}\right)+\dfrac{\partial u}{\partial x}=0 \\ -G\nabla^2 \nu^s - \dfrac{G}{1-2\nu}\dfrac{\partial}{\partial y}\left(\dfrac{\partial u^s}{\partial x}+\dfrac{\partial \nu^s}{\partial y}+\dfrac{\partial w^s}{\partial z}\right)+\dfrac{\partial u}{\partial y}=0 \\ -G\nabla^2 w^s - \dfrac{G}{1-2\nu}\dfrac{\partial}{\partial z}\left(\dfrac{\partial u^s}{\partial x}+\dfrac{\partial \nu^s}{\partial y}+\dfrac{\partial w^s}{\partial z}\right)+\dfrac{\partial u}{\partial z}=0 \\ -\dfrac{\partial}{\partial t}\left(\dfrac{\partial u^s}{\partial x}+\dfrac{\partial \nu^s}{\partial y}+\dfrac{\partial w^s}{\partial z}\right)+\dfrac{K}{\gamma_w}\nabla^2 u=0 \end{cases} \tag{1}$$

The first three equations are the solid particle consolidation differential equations, and the fourth equation is the fluid continuity equation. G is the shear modulus; ν is the solid particle Poisson's ratio; u is the pore fluid stress; γ_w is the fluid unit weight; k is the solid particle penetration coefficient; u^s, ν^s, w^s, and u are, respectively, the displacements in the x, y, z directions and the time; and ∇^2 is the Laplace operator, which can be expressed as:

$$\nabla^2 = \frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2} \tag{2}$$

Under certain primary and boundary conditions, these four unknown variables, u^s, ν^s, w^s, and u, can be solved using Equation (1).