Journal of Petroleum Science and Engineering 139 (2016) 254–263

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Investigation of possible wellbore cement failures during hydraulic fracturing operations

Jihoon Kim [a,b,*], George J. Moridis [b], Eduardo R. Martinez [a]

[a] Harold Vance Department of Petroleum Engineering, Texas A&M University, 3116 TAMU Richardson Building College Station, TX 77843, USA
[b] Earth Sciences Division, Lawrence Berkeley National Laboratory. 1, Cyclotron Road 90R1116, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form
30 September 2015
Accepted 29 January 2016
Available online 5 February 2016

Keywords:
Well instability
Cement failure
Hydraulic fracturing
Shale gas
Coupled flow and geomechanics

ABSTRACT

We model and assess the possibility of shear failure along the vertical well by using the Mohr–Coulomb failure model and employing a rigorous coupled flow-geomechanic analysis. To this end, we take various values of cohesion between the well casing and the surrounding cement to represent different quality levels of cementing operation (low cohesion corresponds to low-quality cement and/or incomplete cementing). The simulation results show that there is very little fracturing when the cement is of high quality. Conversely, incomplete cementing and/or weak cement can cause significant shear failure and evolution of long fractures/cracks along the vertical well. Specifically, low cohesion between the well and cemented areas can cause significant shear failure along the well, while high cohesion does not cause shear failure. The Biot and thermal dilation coefficients strongly affect shear failure along the well casing, and low Young's modulus causes fast failure propagation. Still, for the high quality of the cementing job, failure propagates very little.

When the hydraulic fracturing pressure is high or when permeability increases significantly, low cohesion of the cement can cause fast propagation of shear failure and of the resulting fracture/crack, but a high-quality cement with no weak zones exhibits limited shear failure that is only concentrated near the bottom of the vertical part of the well. Thus, high-quality cement and complete cementing along the vertical well appears to be the strongest protection against shear failure of the wellbore cement and, consequently, against contamination hazards to drinking water aquifers during hydraulic fracturing operations.

1. Introduction

Gas production from shale gas reservoirs has become an important energy resource in the future, due to the abundant amount of gas (Arthur and Layne, 2008; Jenkins and Boyer, 2008). However, extreme low permeability of the shale gas reservoirs requires artificial reservoir stimulation to enhance productivity, such as hydraulic fracturing (Hill and Nelson, 2000; Vermylen and Zoback, 2011). At the same time, environmental impacts induced by the hydraulic fracturing have been raised, for example, contamination of ground water, unstable growth of the hydraulic fractures, seismic risks and reactivation of existing faults, and soil contamination due to proppant chemicals (Zoback et al., 2010; Rutqvist et al., 2013, 2015).

Dusseault et al. (2001) also studied compaction-induced shear failure of the vertical well by fluid production. Shear failure is one of the typical mechanisms of well instability. Incomplete cementing between the well and reservoir formations is considered as one of the high environmental risks of ground water contamination (Zoback et al., 2010). Pressurization at the bottom of the vertical well causes high shear stress along the vertical well and can result in shear slip at the contacting area between the well casing and the cemented zone when the contacting area is poorly cemented. Cracks from shear failure along the well can be a potential path way that can connect deep shale gas reservoirs to shallow aquifers, yielding high permeability.

Failure induced by perturbation of fluid pressure implies strong interaction between flow and geomechanics, and thus coupled flow-geomechanics simulation is required for accurate prediction and better assessment of potential risks induced by shear failure along the well. Pressure of incompressible fluid such as water is sensitive to small change in pore volume, and, in turn, the changes in pressure alter the effective stress regime, which induces material failure (e.g.,

* Corresponding author at: Harold Vance Department of Petroleum Engineering, Texas A&M University, 3116 TAMU Richardson Building College Station, TX 77843, USA.
E-mail addresses: jihoon.kim@tamu.edu (J. Kim), GJMoridis@lbl.gov (G.J. Moridis), waldo49@tamu.edu (E.R. Martinez).

http://dx.doi.org/10.1016/j.petrol.2016.01.035
0920-4105/

Kim et al., 2012). Permeability is also a strong function of the failure status, because material failure creates fractures, which increases permeability significantly by several orders (Bandis et al., 1983; Rutqvist and Stephansson, 2003; Min et al., 2004). Thus, in this study, we rigorously model two-way coupled flow and geomechanics with dynamic failure-dependent permeability.

For the modeling of coupled flow and geomechanics, we use a sequential implicit method, employing the fixed-stress split, which can provide unconditional stability and high accuracy, considering two-way coupling between flow and geomechanics (Kim et al., 2011). Specifically, flow is solved first, fixing the total stress fields and considering the contribution of geomechanics to flow explicitly, and then geomechanics is solved from the solutions obtained at the previous flow step. We employ finite volume and finite element methods for flow and geomechanics in space discretization, respectively, and the backward Euler method in time discretization. We employ the Mohr–Coulomb failure model for elastoplasticity, which is widely used to model failure in cohesive frictional materials, shear failure. We then use dynamic permeability to reflect failure status every time steps. In this study, from various numerical simulations, we will find that there is very little fracturing when the cementing is complete and well-done, whereas incomplete cementing can cause significant shear failure along the vertical well.

2. Mathematical description

We first describe governing equations for fluid-heat flow and geomechanics, followed by couplings in pore volume and permeability. The governing equation for multiphase and multi-component flow comes from mass balance as (e.g., Pruess et al., 1999),

$$\frac{d}{dt}\int_{\Omega} m^k \, d\Omega + \int_{\Gamma} \mathbf{f}^k \cdot \mathbf{n} \, d\Gamma = \int_{\Omega} q^k \, d\Omega, \tag{1}$$

where the superscript k indicates the fluid component. $d(\cdot)/dt$ means the time derivative of a physical quantity $(\cdot)$ relative to the motion of the solid skeleton. m^k is the mass of component k. $\mathbf{f}^k$ and q^k are its flux and source terms on the domain Ω with a boundary surface Γ, respectively, where $\mathbf{n}$ is the normal vector of the boundary.

The fluid mass of component k is written as

$$m^k = \sum_J \phi S_J \rho_J X_J^k, \tag{2}$$

where the subscript J indicates fluid phases. ϕ is the true porosity, defined as the ratio of the pore volume to the bulk volume in the deformed configuration. S_J, ρ_J, and $X_J{}^k$ are saturation, density of phase J, and the mass fraction of component k in phase J, respectively.

The mass flux term is obtained from

$$\mathbf{f}^k = \sum_J \left(\mathbf{w}_J^k + \mathbf{J}_J^k \right), \tag{3}$$

where $\mathbf{w}_J^k$ and $\mathbf{J}_J^k$ are the convective and diffusive mass flows of component k in phase J, respectively. For the liquid phase, $J=L$, $\mathbf{w}_J^k$ is supplemented by Darcy's law, which includes the Klinkenberg effect for the case of gas. $\mathbf{J}_J^k$ is determined by Fick's law with diffusion and hydrodynamic dispersion.

Heat flow comes from energy (heat) balance, as

$$\frac{d}{dt}\int_{\Omega} m^H \, d\Omega + \int_{\Gamma} \mathbf{f}^H \cdot \mathbf{n} \, d\Gamma = \int_{\Omega} q^H \, d\Omega, \tag{4}$$

where the superscript H indicates the heat component. m^H, $\mathbf{f}^H$, and q^H are heat, its flux, and source terms, respectively. The term m^H is the heat accumulation term, and is expressed as

$$m^H = (1-\phi)\int_{T_0}^{T} \rho_R C_R \, dT + \sum_J \phi S_J \rho_J e_J, \tag{5}$$

where ρ_R, C_R, T and T_0 are density, heat capacity, temperature of the porous medium, and reference temperature, respectively. e_J denotes specific internal energy of phase J. The heat flux is written as

$$\mathbf{f}^H = -\mathbf{K}_H \, \mathbf{Grad} \, T + \sum_J h_J \mathbf{w}_J, \tag{6}$$

where $\mathbf{K}_H$ is the composite thermal conductivity of the porous media. **Grad** is the gradient operator. The specific internal energy, e_J, and enthalpy, h_J, in phase J become, respectively,

$$e_J = \sum_k X_J^k e_J^k, \quad h_J = \sum_k X_J^k h_J^k. \tag{7}$$

Geomechanics is based on the quasi-static assumption (Coussy, 1995), written as

$$\mathrm{Div}\, \boldsymbol{\sigma} + \rho_b \mathbf{g} = \mathbf{0}, \tag{8}$$

where Div is the divergence operator. $\boldsymbol{\sigma}$ is the total stress tensor, and ρ_b is the bulk density. Tensile stress is positive in this study. The infinitesimal transformation is used to allow the strain tensor, $\boldsymbol{\varepsilon}$, to be the symmetric gradient of the displacement vector, $\mathbf{u}$,

$$\boldsymbol{\varepsilon} = \frac{1}{2}\left(\mathbf{Grad}^T \, \mathbf{u} + \mathbf{Grad} \, \mathbf{u} \right). \tag{9}$$

Then, considering mass, energy, linear momentum balances, we focus on non-isothermal multiphase flow (i.e., water–gas flow) with the elastoplastic geomechanics in this study, using the following constitutive relations of thermo-poro-mechanics.

3. Shear failure and coupling in permeability and porosity

Leaking of the injected water induces pressurization near the wells, as shown in Fig. 1. Pressurization at the bottom of the vertical well causes high shear stress along the vertical well and can result in shear slip at the contacting area between the well casing and the cemented zone when the contacting area is poorly cemented. Shear failure along the well can create high permeable area that can connect deep shale gas reservoirs to the aquifers.

For the modeling of shear failure in this study, we use the Mohr–Coulomb model, which is widely used to model failure of cohesive frictional materials. The Mohr–Coulomb model is given as

$$\begin{aligned} f &= \tau_m' - \sigma_m' \sin \Psi_f - c_h \cos \Psi_f \le 0, \\ g &= \tau_m' - \sigma_m' \sin \Psi_d - c_h \cos \Psi_d \le 0, \end{aligned} \tag{10}$$

$$\sigma_m' = \frac{\sigma_1' + \sigma_3'}{2} \quad \text{and} \quad \tau_m' = \frac{\sigma_1' - \sigma_3'}{2}, \tag{11}$$

where σ_1', σ_2', and σ_3' are the maximum, intermediate, and minimum principal effective stresses, respectively. c_h is the cohesion. f and g are the yield and plastic potential functions, respectively. Ψ_f, and Ψ_d are the friction angle, and the dilation angle, respectively.

Once shear failure occurs, we employ the permeability model motivated by the cubic law (Witherspoon et al., 1980; Rutqvist and Stephansson, 2003) for the created fracture, written as (e.g., for the case of single water phase),