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A fully coupled geomechanics and fluid flow model for proppant pack failure and fracture conductivity damage analysis

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ABSTRACT

One reason for observed reductions in the conductivity of hydraulic fractures is failure of the proppant pack. Proppant deformation, crushing, or embedment can decrease the fracture width and conductivity. In this paper, the continuity and momentum balance equations were fully coupled to simulate the transient phenomena involving fluid flow through a deformable porous proppant pack. Porous media displacement, water pressure, and gas pressure were derived as primary unknowns. The governing equation was discretized using the finite element method and solved numerically. In this model, the proppant pack and formation rocks were treated as two different types of continuous porous media (Biot type). Proppant deformation, crushing, and embedment could be identified through the geomechanical model, while the damage effects on gas/oil production would be studied through the fluid-flow model. Analysis of proppant deformation and crushing was based on the proppant pack stress–strain behavior. The displacement of the fracture-formation interface represented both the deformation of proppant and rock solids around fracture surface. Mohr–Coulomb failure was used as the criterion for proppant crushing. Effects of proppant damage were evaluated on proppant pack porosity and permeability. The model can be applied generally in hydraulically fractured reservoirs with proper inputs. In this paper, we used a fractured tight sand gas reservoir as a study case. The pressure distribution as well as proppant pack deformation are illustrated in the paper. Proppant pack mechanical behavior was found to be sensitive to the fluid flow pressure. Proppant near the wellbore has a higher likelihood of being crushed.

1. Introduction

Proppants, which are usually sand particles but can also be synthetic ceramic material, are injected with fracturing fluid during well stimulation treatments. The purpose is to hold the fracture open after the high-pressure fluid is released to flow back to surface. Under the in-situ stresses, proppant can deform, crush or embed into the formation rock, which decreases the hydraulic fracture width and conductivity (Gidley et al., 1995, Lacy et al., 1997). In some cases, the loosely packed proppant can flow back to surface. It is believed that the failure of proppant pack can result in an early production decrease which is quite common in tight sandstone and shale gas reservoirs.

Proppant damage is difficult to be quantified. Significant amount of researches have been conducted on lab-based proppant strength tests. Most of these results were obtained under ideal lab conditions which are API Recommended Practice 19C (RP19C, identical to ISO13803-2 standard). A ten inch long, one and a half inch wide conductivity cell containing sandwiched "rock-proppant-rock" samples is used to analyze proppant damage and fracture conductivity loss. The lab test results can deviate from field tests by one order of magnitude (Palisch et al., 2009). The lab tests are time and money consuming, and not applicable in evaluating proppant damage effects on reservoir scale. Traditional partially coupled numerical models (Osholake et al., 2011) using analytical or empirical correlations can not accurately describe the damage mechanism. To fully quantify the effect of the proppant damage, a fully coupled model is needed, in which the deformation of proppant as well as the gas and water pressure are solved simultaneously.

2. Governing equation

The purpose of using a fully coupled model is to assess how the changes in pore pressure affect stresses in the reservoir and the

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surrounding formation. Our specific goal is to explore how proppant pack deforms, and the associated fracture conductivity losses. The research focuses on the propped fracture conductivity and treats the settled proppant as a proppant pack. Both the proppant pack and formation rock are assumed to be linear poroelastic media. Effective stresses perturbations generate strain which can affect the pore space of the solid media. And changes of pore space volume can induce changes in the diffusivity in the fluid-flow equation.

Mass balance equation for solid phase (superscripted by s) can be expressed as the following equations.

$$\frac{\partial(1-\phi)\rho^s}{\partial t}+\nabla\cdot[(1-\phi)\rho^s v^s]=0 \tag{1}$$

where ρ is the density; ϕ is the porosity; v is the velocity, and t is time. As the vector calculus identity holds, $\nabla\cdot(\rho_s V^s)=\rho^s{*}\nabla\cdot v^s+\nabla\cdot\rho_s{*}v^s$. Carrying out the time derivatives, neglecting the gradient of $(1-\phi)\ \rho^s$, and dividing by ρ^s, Eqn. (1) becomes

$$\frac{1-\phi}{\rho^s}\frac{\partial\rho^s}{\partial t}-\frac{\partial\phi}{\partial t}+(1-\phi)\nabla\cdot v^s=0 \tag{2}$$

For the fluid phases (superscripted by π), the mass balance equation can be expressed as:

$$\frac{\partial(\phi s_\pi\rho^\pi)}{\partial t}+\nabla\cdot[\phi s_\pi\rho^\pi v^\pi]=0 \tag{3}$$

Introducing relative acceleration ($a^{\pi s}$) and velocity concept (O.C. Zienkiewicz, et al., 1999),

$$a^\pi=a^s+a^{\pi s}$$

where the acceleration terms (a) can be defined from the linear momentum balance equation

$$\rho a^s+\phi s_w\rho^w a^{ws}+\phi s_g\rho^g a^{gs}=\nabla\cdot\sigma+\rho g \tag{4}$$

$$\rho=(1-\phi)\rho^s+\phi s_w\rho^w+\phi s_g\rho^g \tag{5}$$

The relative fluid phase velocity can be defined accordingly

$$v^\pi=v^s+v^{\pi s} \tag{6}$$

Then the modified Darcy equation can be

$$\phi s_\pi v^{\pi s}=-\frac{kk^{r\pi}}{\mu^\pi}[\nabla\cdot p^\pi-\rho^\pi(g-a^s-a^{\pi s})] \tag{7}$$

For the liquid phase, after dividing equation by $s_\pi\rho^\pi$, applying the vector calculus identity, and neglecting $\nabla(\phi s_\pi\rho^\pi)$, Eqn. (3) becomes:

$$\frac{\partial\phi}{\partial t}+\frac{\phi}{\rho^\pi}\frac{\partial\rho^\pi}{\partial t}+\frac{\phi}{s_\pi}\frac{\partial s_\pi}{\partial t}+\frac{1}{s_\pi\rho^\pi}\nabla\cdot(\phi s_\pi\rho^\pi v^{\pi s})+\phi\nabla\cdot v^s=0 \tag{8}$$

The summation of Eqns. (2) and (8) will yield the mass balance equation of the system:

$$\frac{1-\phi}{\rho^s}\frac{\partial\rho^s}{\partial t}+\nabla\cdot v^s+\frac{\phi}{\rho^\pi}\frac{\partial\rho^\pi}{\partial t}+\frac{\phi}{s_\pi}\frac{\partial s_\pi}{\partial t}+\frac{1}{s_\pi\rho^\pi}(\phi s_\pi\rho^\pi v^{\pi s})=0 \tag{9}$$

In this case, the system is treated as isothermal. Thus the solid density can be assumed to be determined on pressure and first invariant of stress (Lewis and Schretler, 1998).

$$\frac{\partial\rho^s}{\partial t}=\frac{\rho^s}{1-\phi}\left[(\alpha-\phi)\frac{1}{K_S}\frac{\mathrm{d}^s p^s}{\mathrm{d}t}-(1-\alpha)\nabla\cdot v^s\right] \tag{10}$$

For multi-phase flow system, the pressure to the solid phase can be concluded as (Hassanizadeh and Gray, 1993):

$$p^s=\sum_{i=1}^{n}p^i s_i \tag{11}$$

Accordingly the effective stress of the system can be expressed as:

$$\sigma''=\sigma+\mathbf{m}\alpha\sum_{i=1}^{n}p^i s_i \tag{12}$$

Assuming of solids' velocity are mainly due to its deformation which is true for the settled particles, then

$$\nabla\cdot v^s=\mathrm{d}\varepsilon=m^T L\frac{\partial u}{\partial t} \tag{13}$$

Put Equations (5), (7), (10), and (13) into (9), yields

$$(\alpha-\phi)\frac{1}{K_S}\frac{\mathrm{d}^s p^s}{\mathrm{d}t}+\alpha m^T L\frac{\partial u}{\partial t}+\frac{\phi}{\rho^\pi}\frac{\partial\rho^\pi}{\partial t}+\frac{n}{s_\pi}\frac{\partial s_\pi}{\partial t}+\frac{1}{s_\pi\rho^\pi}\left(\rho^\pi\frac{kk^{r\pi}}{\mu^\pi}[-\nabla p^\pi+\rho^\pi(g-a^s-a^{\pi s})]\right)=0 \tag{14}$$

The modified continuity equation of the system (Eqn. (14) can be further assigned to each fluid phase by taking density equation (Eqn. (5) in to consideration.

Another governing equation for the system is the balance of momentum equation in aspect of total stresses:

$$L^T\sigma+\rho g=0 \tag{15}$$

Where the L is the stress differential operator; σ is the force applied on solids as Eqn. (12); ρ is the density from Eqn. (5).

The primary unknowns for the governing equations (Eqns. (14) and (15)) are displacements, fluid phase pressures. The equations need initial pressure and deformation of the system. Boundary conditions as specified stress and flux are also required. The governing equations are further discretized in Finite element method way by weighting residues into zero over domain and boundary.

2.1. Stress sensitive permeability and porosity

A clear understanding of rock stress and its effect on permeability and porosity is important in a coupled simulation where fluid production causes a significant increase in the effective stress within a reservoir. In this paper, the correlations we used to investigate the porosity and permeability change would be (Schutjens, and Hanssen, 2004)

$$\Delta\phi=\frac{\varepsilon_b(\phi_0-1)}{1-\varepsilon_b} \tag{16}$$

ε_b is the strain which is the main unknown we solved in the momentum governing equation. ϕ_0 is the initial porosity. To further evaluate the relationship between permeability and deformation, we use the experimental relationship of Carmen–Kozeny to model the influence of porosity changes (due to deformation) on permeability integrated with stress field. As we are focusing on the settled proppant pack which can be similarly treated as a porous rock with solids tightly aggregated. The Carmen–Kozeny equation can describe such a proppant pack under the assumption of linear