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Phase-field modeling of proppant-filled fractures in a poroelastic medium

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Abstract

In this paper we present a phase field model for proppant-filled fractures in a poroelastic medium. The formulation of the coupled system involves four unknowns: displacements, phase field, pressure, and proppant concentration. The two-field displacement phase-field system is solved fully-coupled and accounts for crack irreversibility. This solution is then coupled to the pressure equation via a fixed-stress iteration. The pressure is obtained by using a diffraction equation where the phase-field variable serves as an indicator function that distinguishes between the fracture and the reservoir. The transport of the proppant in the fracture is modeled by using a power-law fluid system. The numerical discretization in space is based on Galerkin finite elements for displacements and phase-field, and an enriched Galerkin method is applied for the pressure equation in order to obtain local mass conservation. The concentration is solved with cell-centered finite elements. Nonlinear equations are treated with Newton's method. Our developments are substantiated with several numerical examples in two and three dimensions.

Keywords: Phase field fracture; Hydraulic fracturing; Proppant transport; Quasi-Newtonian flow model

1. Introduction

Murray Roth, a VP at Global Consulting, has called proppant the greatest oilfield innovation of the 21st century. A proppant is a solid material, typically sand, treated sand or man-made ceramic materials, designed to keep an induced hydraulic fracture open, during or following a fracturing treatment. The objective of a hydraulic fracturing treatment in the oil industry is to increase the flow area exposed to the formation and then to connect the flow area to the wellbore along a high permeability path. Proppant is added to a fracking fluid which may vary in composition depending on the type of fracturing used, and can be gel, foam or slickwater-based. Although hydraulic fracturing was first performed

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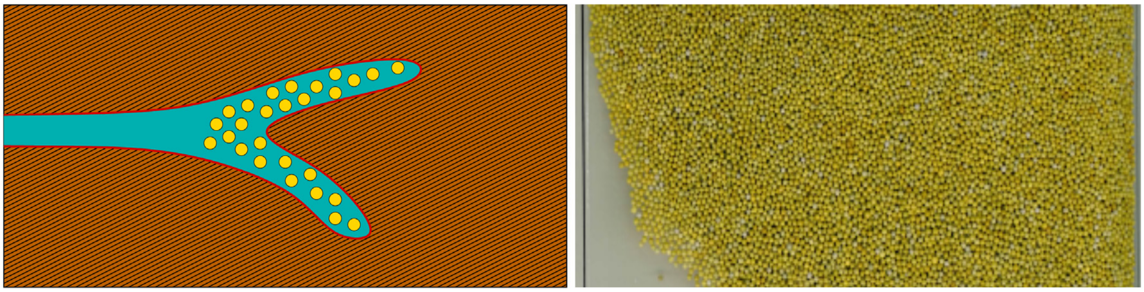

Fig. 1. Illustration of proppant usage (yellow coated grains) preventing the fracture from closing (left). At right, real proppant grains used in hydraulic fracturing are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in 1947 (in Kansas, using sand from the Arkansas river), wide-spread experimentation did not occur until the Barnett Shale play in the 80s, and usage has exploded in the first decade of this century. Expansion was aided by a landmark study conducted by the EPA (environmental protection agency) in 2004 which found that hydraulic fracturing posed no threat to underground drinking water supplies. Shortly afterwards, hydraulic fracturing was exempted from the Safe Drinking Water Act by the Bush administration in the Energy Policy Act of 2005.

Hydraulic fracturing has become a key element of natural gas development worldwide, and countries such as the United States, Canada, India, England and China are actively pursuing implementation of this technology to tap into this new source of energy. However, like any advanced technology, it has also raised questions about its long-term impact on the environment. Thus debate and research will continue well into the future and the role of more advanced models will be required for new and upcoming regulations.

The quality of proppant is designed to maintain lasting, high permeability under conditions of in situ stress and temperature. Since the goal in field operations is to distribute proppant optimally, accurate and efficient numerical models are essential in representing proppant transport in fractures (see Fig. 1). Here simulation is challenging because of the complex interactions between the fluid, particles and fracture walls. As described by [1] in the modeling of hydraulic fracturing, a variety of physical processes such as fluid flow, stress induced by fracture deformation, complex fluid rheology, and fracture propagation are occurring simultaneously. Slurry flow, gravitational settling, and proppant transport modeling for hydraulic fractures are currently poorly understood and modeling capability limited.

Mixing proppant with a Newtonian fluid has been investigated in [1–4], and with polymers in [5–8] to name a few. These numerical studies have been performed using boundary element methods, discrete fracture networks or extended/generalized finite elements and have mainly treated 2D planar fractures. A survey of different models for fracture propagation can be found in [9] and our focus in this paper will be on phase-field fracture models. Presently, the latter approach is subject of active research in both mathematical theory and applications. Based on variational principles, the phase-field technique provides an elegant way to approximate lower-dimensional surfaces and discontinuities.

Rewriting Griffith's model [10] for brittle fracture in terms of a variational formulation was first accomplished by Francfort and Marigo [11]. Later, in [12,13], the authors refined modeling and material law assumptions to formulate an incremental thermodynamically consistent phase-field model for fracture propagation. Computational techniques, finite element analysis, and multiple examples and benchmarks from mechanical engineering have been proposed and studied in [14,15,12,13,16–23]. Recent advances and numerical studies towards hydraulic fracturing and other multiphysics applications including thermo-elastic–plastic solids and coupling with a reservoir simulator have been considered in [24–28,9,29,30]. Clearly, these cited works demonstrate that phase-field fracture modeling has tremendous potential tackling practical field problems.

More specifically, phase-field fracture modeling offers many advantages such as a fixed-grid topology that avoids expensive remeshing for resolving the exact fracture location. Thus, the model can be implemented easily to simulate both 2D and 3D crack propagation [18,19,31,27,28]. Therein, fracture nucleation, propagation, kinking, curvilinear path, branching, joining and handling large fracture networks are intrinsically determined. Moreover, the phase-field variable can be used to compute the crack opening displacement (e.g., [32]) as well as serving as an indicator function to formulate a pressure diffraction model in order to couple with phase-field fracture with other multiphysics phenomena [25]. On the other hand, the diffusive transition zone tends to smear out the sharp crack surface and the

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