URTeC: 2927

# Hydraulic Fracture Propagation Simulations in Porous Media with Natural Fractures by IPACS

Mary F. Wheeler*[1], Sanghyun Lee[2], [1]The University of Texas at Austin, [2]Florida State University.



This paper was prepared for presentation at the Unconventional Resources Technology Conference held in Austin, Texas, USA, 20-22 July 2020.



## Abstract

Recent studies reveal that unconventional reservoirs contain complex natural fracture networks. Thus, in stimulating hydraulic fractures, it is important to study the interactions between natural fractures and hydraulic fractures. The goal of this work is to describe practical aspects of recent advances in the domain of geomechanical and discrete fracture network coupling, stimulation modeling, treating large number of fractures, adaptive mesh refinement methods, and overall fracture management within an unconventional setting. The computational framework is developed as an in-house code named IPACS (Integrated Phase-field Advanced Crack Propagation Simulator). Here, we describe a diffusive adaptive finite element phase field approach for modeling natural and hydraulic fractures. High fidelity finite element methods are employed to model multiphase flow with local mass conservation and dynamic mesh adaptivity. Geomechanics approximated by a continuous Galerkin finite element method is coupled to multiphase flow approximated by an enriched Galerkin finite element method by applying an iteratively coupled scheme.

## Introduction

Through extended field experimentation recent field observations have shown that current stimulation models fall short in predicting hydraulic fracture geometries, proppant placement and transport, flowback, and the effects of stress shadowing and parent/child fracture parents. Moreover, most current simulators are unable to treat fracture propagation and production of flow and mechanics in a seamless fashion. Effects in including geochemistry are generally ignored except in very simple models. Thus, there is a need to demonstrate recent research efforts that can assist in predicting and modelling realistic stimulation processes. Consequently, engineering stimulated reservoir volume including proppant placement and/or acid fracturing treatments, can be achieved within computationally realistic frameworks, which can be used for reservoir management studies. In these research fields, the Center for Subsurface Modeling (CSM) in collaboration with other international institutes, has been contributing numerous studies. The emphasis has been on rigorous mathematical modeling, physics based discretizations, and numerical simulations. A robust and efficient computational framework for reservoir fracture modeling was developed resulting in IPACS - an integrated phase-field advanced crack propagation simulator. In this paper we describe and illustrate the main features of IPACS [1].

In this presentation we focus on a phase field approach for fracture stimulation. The phase-field methodology is a powerful tool for modeling the evolution of microstructures and their interactions of defects in a wide range of materials and physical models. The accurate simulation of fracture evolution in solids is a major challenge for computational algorithms, in large part due to crack paths that are generally unknown a priori. In this regard, phase-field approaches have shown great potential with their ability to automatically determine the direction of crack propagation through minimization of an energy functional. The phase-field framework naturally handles the emergence of phenomena such as crack nucleation and branching without the need to introduce additional criteria. In particular, formulations derived from variational theory have received a lot of attention from the applied mechanics community due to its strong ties to Griffith's theory [2] for brittle fracture.

Phase-field models belong to the category of continuum approaches for fracture propagation, utilizing a diffuse representation of cracks in place of actual discontinuities. The amount of crack regularization is controlled via a prescribed length scale, which constitutes an additional parameter of the model. These methods can be implemented to simulate large- scale evolution of material microstructure and defect motion without the need to explicitly track interfaces. Cracks and their growth emerge as solutions to the governing partial differential equations of the model. A particularly unique and striking feature of the approach is that all calculations are performed entirely on the initial, un-deformed configuration. There is no need to disconnect, eliminate, or move elements or introduce additional discontinuous basis functions, as is commonly done in the discrete crack computational fracture mechanics approaches. This results in a significant simplification of the numerical implementation, and a simple and direct pathway from two-dimensional to three-dimensional applications.

One of the major advantages of the phase field based IPACS is that this framework is easily coupled with the reservoir simulator for the predictive reservoir production, and with the inverse optimization algorithm for history-match process. Moreover, IPACS has satisfies the following/model capabilities:

- an adequate meshing, well adapted to natural fracture geometries as they are characterized, including potential geometries induced by stimulation.
- a stimulation model which couples adequately geomechanical effects (stimulation capacity due to near/far geomechanical interactions).
- an accurate way to couple nonlinear flow and mechanics models using a posteriori adaptivity
- an accurate account of physical processes occurring during production, especially matrix fracture interaction.

In this paper, we demonstrate many of the above aspects, namely both the effects and the ease of implementation of coupling multiphase flow and mechanics in a fractured medium using a phase field approach. In addition, we treat the interactions between hydraulic and natural fractures. The latter are treated in a diffusive fashion.

**Coupling Flow with Phase Field Fractures**

This approach is described by applying an indicator scalar function also called as a phase-field $\phi \in [0,1]$ to define fractures; see [3, 4]. Here, $\phi$ is referred to as the phase function and $\phi = 0$ and $\phi = 1$ represent broken (fracture) and unbroken (reservoir) zones respectively. In addition, there is a transition zone $\phi \in (0,1)$ with the length parameter $\epsilon$. A detailed discussion of a natural fracture network and adaptivity can be found in [5].

In the computational domain $\Lambda$, the energy functional based on the poroelasticity Biot system [6, 7] is defined as

$$E(\boldsymbol{u},\varphi,p)=\int_{\Lambda}\frac{1}{2}g(\phi)(\sigma(\boldsymbol{u}):\epsilon(\boldsymbol{u}))dV-\int_{\partial\Lambda}(\tau+p\boldsymbol{n})\cdot\boldsymbol{u}\,dA+\int_{\Lambda}\phi^2(\nabla p\cdot\boldsymbol{u})dV$$
$$+\int_{\Lambda}\phi^2\big((1-\alpha)p\cdot\nabla\boldsymbol{u}\big)dV+G_c\int_{\Lambda}\left(\frac{1}{2\epsilon}(1-\phi)^2+\frac{\epsilon}{2}(\nabla\phi)^2\right)dV,$$

where it models the balance between elastic strain energy and crack surface energy. Here $\boldsymbol{u}$ is the displacement, $\tau$ is the boundary force, and $\sigma(\boldsymbol{u})$ is the elastic stress tensor defined as $\sigma(\boldsymbol{u}) \coloneqq 2\mu e(\boldsymbol{u}) + \lambda tr\big(e(\boldsymbol{u})\big)\boldsymbol{I}$, where $\mu$ and $\lambda$ are lame parameters, and $e(\boldsymbol{u})$ is the symmetric strain tensor given as $e(\boldsymbol{u}) \coloneqq 0.5\big(\nabla\boldsymbol{u}+\nabla\boldsymbol{u}^{\boldsymbol{T}}\big)$. In addition, $p$ is the pressure, $\boldsymbol{n}$ is the outward normal vector of the domain, $\alpha$ is the Biot's coefficient, and $G_c$ is the critical energy release rate or fracture toughness criteria. The $g(\phi)$ is the degradation function, which is set as $g(\phi)=(1-\kappa)\phi^2+\kappa$, with $\kappa$ being a small positive regularization parameter. The last term represents the fracture energy through the Ambrosio-Tortorelli elliptic functionals by replacing the Hausdorff measure in a computable form [8, 9, 10]. Then the first formulation to solve is the following constrained minimization problem:

$$\text{mininize}\, E\ (\boldsymbol{u},p,\phi)\ \text{subject to}\ \ \partial_{\mathrm{t}}\phi\leq 0,$$

where the last condition is known as the irreversibility condition (i.e. to fractures allowed only to propagate but not to heal). This minimization equation is solved by utilizing a primal-dual active set method [11] and continuous Galerkin finite element methods.

In order to formulate the flow equation in both the reservoir and the fracture, we employ the pressure diffraction system [7]. In the pressure diffraction system, the underlying Darcy flow equations have the same structure in both the porous media and the fracture. However, using the phase field indicator variable allows different treatments between reservoir flow and fracture flow. In addition, in the reservoir (or fracture) two phase aspects can be treated within this framework. We denote by $\Omega_F$ and $\Omega_R$, for the reservoir and the fracture subdomains. More details to describe these domains are discussed in [12]. The pressure diffraction formulation that we solve is described as

$$\rho_R\partial_t\left(\frac{1}{M}p_R+\alpha\nabla\cdot\boldsymbol{u}\right)-\nabla\cdot\frac{K_R\rho_R}{\eta_R}(\nabla p_R-\ \rho_R\boldsymbol{g})=q_R\qquad in\ \Omega_R,$$

$$\rho_F\partial_t(c_Fp_F)-\nabla\cdot\frac{K_F\rho_F}{\eta_F}(\nabla p_F-\ \rho_F\boldsymbol{g})=q_F\qquad in\ \Omega_{F,}$$

where $\rho$ is the fluid density, $M$is Biot's modulus, $\eta$ is the fluid viscosity, $c_F$is fluid compressibility, and $q$is the source/sink term. The subscript indicates either the reservoir zone ($R$) and the fracture zone ($F$). Here, $K_R$ is the permeability in the reservoir and $K_F$ is the permeability computed by the width of the fracture [13]. This flow equations can be extended to consider quasi-linear flow for proppant transport coupled with the concentration transport equation as demonstrated in [14]. Moreover, the relative permeability and capillary pressure to consider two phase flow system with the saturation formulation in the propagating fracture is discussed in [15].

An enriched Galerkin (EG) [16], a simplified discontinuous Galerkin (DG) approximation, is employed for the spatial discretization of the above pressure diffraction system. EG provides locally and globally conservative fluxes and preserves local mass balance. Recently, EG has been successfully employed to realistic multiscale and multi-physics applications.

## 4. Numerical Example

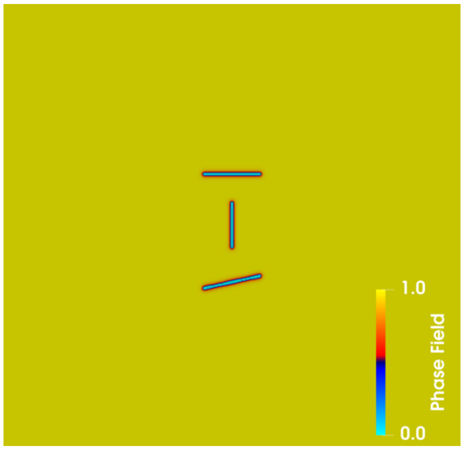


Figure 1. An initial setup

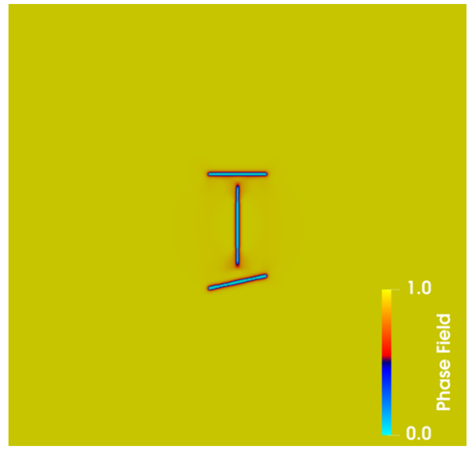


Figure 2. n=15

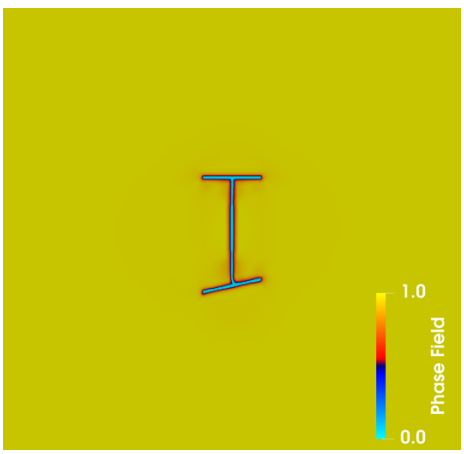


Figure 3. n=50

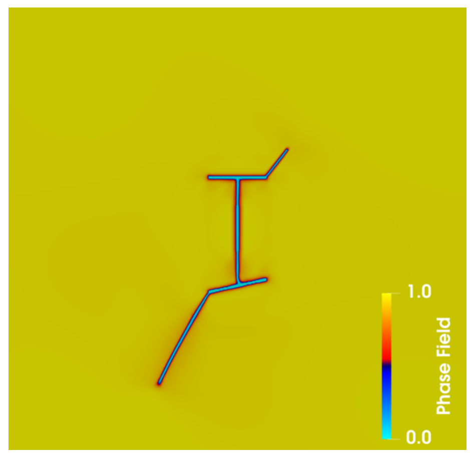


Figure 4. n=120

A schematic setup for the numerical experiments is illustrated in Figure 1, where the initial condition is described with the two natural fractures at the top and bottom of the hydraulic fracture, which is placed at the middle. The location of the midpoint of the injection point for the hydraulic fracture is in the center of the domain $\Lambda$. The material properties for the injected two-phase flow and the solid materials are taken from [17]. In this case, two natural fractures have the same length but the bottom fracture is tilted.

The simulated phase-field values for the propagating fractures for each time step n are presented in Figure 2-4. First, the hydraulic fracture propagates until it joins with the existing natural fractures. Due to the pressure drop when the hydraulic and natural fractures meet, it takes a while to accumulate enough pressure to initiate the new branching. In other words, the fracture propagation speed from Figure 1 to 3 is much faster than Figure 3 to 4 since it takes much longer time to initiate the branching of the fractures at the tip of the natural fractures in Figure 4. The branching of the fracture presents an interesting phenomenon as shown in Figure 4. This example illustrates the capabilities of the proposed algorithm in handling multiphase flow and joining and branching of multi fractures in porous media.

## References


[1] M. F. Wheeler, T. Wick and S. Lee, "IPACS: Integrated Phase-Field Advanced Crack Propagation Simulator. An adaptive, parallel, physics-based-discretization phase-field framework for fracture propagation in porous media," *Computer Methods in Applied Mechanics and Engineering,* 2020.

[2] A. Griffith, "The phenomena of rupture and flow in solids," *Phil. Trans. R. Soc.,* p. 163–198, 1921.

[3] C. Miehe, F. Welschinger and M. Hofacker, "Thermodynamically consistent phase-field models of fracture: variational principles and multi-field fe implementations," *Int. J. Numer. Methods Eng.,* p. 1273–1311, 2010.

[4] A. Mikelic, M. F. Wheeler and T. Wick, "A quasi-static phase-field approach to pressurized fractures," *Nonlinearity,* pp. 1371-1399, 2015.

[5] S. Srinivasan, S. Lee, M. Wheeler and T. Wick, "Initialization of phase-field fracture propagation in porous media using probability maps of fracture networks," *Mechanics Research Communications,* pp. 16-23, 2017.

[6] M. A. Biot, "General Theory of Three-Dimensional Consolidation," *Journal of Applied Physics,* 1941.

[7] A. Mikelic, M. F. Wheeler and T. Wick, "Phase-field modeling of a fluid-driven fracture in a poroelastic medium," *Computational Geosciences,* 2015.

[8] L. Ambrosio and V. Tortorelli, "On the approximation of free discontinuity problems," 1992.

[9] B. Bourdin, G. A. Francfort and J.-J. Marigo, "Numerical experiments in revisited brittle fracture," *Journal of the Mechanics and Physics of Solids,* 2000.

[10] J.-J. G.A.Francfort, "Revisiting brittle fracture as an energy minimization problem," *Journal of the Mechanics and Physics of Solids,* 1998.

[11] T. Heister, M. F. Wheeler and T. Wick, "A primal–dual active set method and predictor–corrector mesh adaptivity for computing fracture propagation using a phase-field approach," *Comput. Methods Appl. Mech. Engrg.,* 2015.

[12] S. Lee, M. F. Wheeler and T. Wick, "Pressure and fluid-driven fracture propagation in porous media using an adaptive finite element phase field model," *Computer Methods in Applied Mechanics and Engineering ,* 2016.

[13] S. Lee, M. F. Wheeler and T. Wick, "Iterative coupling of flow, geomechanics and adaptive phase-field fracture including a level-set crack width approach," *Journal of Computational and Applied Mathematics,* vol. 314, pp. 40-60, 2017.

[14] S. Lee, A. Mikelic, M. F. Wheeler and T. Wick, "Phase-field modeling of proppant-filled fractures in a poroelastic medium," *Computer Methods in Applied Mechanics and Engineering ,* no. 312, pp. 509-541, 2016.

[15] S. Lee, A. Mikelic, M. F. Wheeler and T. Wick, "Phase-field modeling of two phase fluid filled fractures in a poroelastic medium," *SIAM Multiscale Modeling & Simulation,* vol. 16, no. 4, pp. 1542-1580, 2018.

[16] S. Lee, Y. Lee and M. F. Wheeler, "A locally conservative enriched galerkin approximation and efficient solver for elliptic and parabolic problems," *SIAM Journal on Scientific Computing,* vol. 38, no. 3, pp. A11404-A1429, 2016.