Hydraulic Fracturing: Modeling, Simulation, and Experiment

Anthony Peirce (University of British Columbia),
Andrew Bunger (University of Pittsburgh),
Emmanuel Detournay (University of Minnesota),
Egor Dontsov (University of Houston),
Dmitry Garagash (Dalhousie University)

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The past decade has seen a significant change in the global energy landscape, largely due to hydraulic fracturing (HF) that has made the extraction of hydrocarbons from gas-rich shale formations economically viable. This process has been enabled by new drilling technology that makes it possible to generate multiple hydraulic fractures from horizontal wells. The rapid expansion of this class of HF is creating concerns about its impact on the environment. Questions are also being raised whether hydraulic fractures could breach impermeable barriers that isolate aquifers from the hydrocarbon bearing formations, thus imperiling the supply of fresh groundwater, or whether they could induce significant seismic events. There are also concerns whether the engineering process has been designed to optimize the recovery of hydrocarbons. The lack of simulation tools that can provide realistic predictions of the geometry and hydraulic conductivity of the HF that have been created and a lack of techniques to characterize these fractures from *in situ* measurements is fueling these concerns. A BIRS workshop was therefore convened to gather input from industry practitioners as well as academic and industry researchers to accelerate the scientific development of the analysis tools required to address these concerns.

1 Overview of the Field

Despite a long series of investigations on the mechanics of fluid-driven fractures since 1950s, it is only over the last two decades that a coherent understanding of the critical mechanisms at play has emerged. It has been shown that the propagation of a hydraulic fracture is governed by strong nonlinearities associated with fluid flow in the fracture, non-local elastic deformation, fluid leak-off in the surrounding rock, and the fracture propagation criterion [3]. Indeed, even the simplest mathematical model for a single HF propagating in a homogeneous elastic medium involves a coupled system of degenerate nonlinear integro-partial differential equations with a complex multi-scale structure [4, 12, 5, 8, 9, 10, 11]. These equations also involve a singular free boundary problem, in which the front velocity can only be determined by evaluating a distinguished limit. Technical issues brought about by the strong nonlinearity and time-dependence of the governing equations, as well as those associated with the moving boundary problem have hindered the development of efficient computational algorithms to simulate [1, 15] (i) the propagation of multiple hydraulic fractures in complex media and (ii) the transport of proppant (e.g. sand) particles that are added to the injected fluid to create a permeable pathway for hydrocarbon extraction. In order to test these analytic and numerical models, considerable effort has been devoted to performing hydraulic fractures in well controlled laboratory experiments [14].

2 Recent Developments

Capturing the propagation, interaction, and possible intersection of multiple arbitrary fracture surfaces in a complex solid medium presents the numerical modeler with formidable challenges. Because of the considerable public interest, the development of new numerical models for this purpose has become an area of intense research. These models can be classified into two broad categories: continuum models that treat the solid and the fluid as continuous media [3] and discrete models that treat the solid as a collection of particles in a lattice connected by springs [2], and the fluid as either a continuum or as modeled explicitly as discrete particles. The classical approach to continuum HF modeling has considered boundary integral equation (BIE) formulations of explicit cracks in a homogeneous or piecewise homogeneous elastic medium. This approach has reached some maturity and can capture the multiscale behavior that takes place in the vicinity of the fracture tip [6], but is limited to linear elastic materials and rapidly loses its advantages when dealing with multiple interacting fractures and heterogeneous media. Fully coupled eXtended Finite Element Method (XFEM) models [7, 13] have also been developed that can model heterogeneous solid media and can capture multiscale behavior. However, since the BIE and XFEM formulations rely on explicit representation of fracture surfaces, capturing the propagation and intersection of these in 3D is challenging. Recently, a class of phase field [16] or smeared crack models has also been developed, in which fractures are not modelled explicitly but rather by distributed damage that is represented by a field variable. The primary advantage of both phase field and discrete models is that they are able to capture the evolution and interaction of complex fracture geometries with significantly less effort than the continuum models in which cracks are modelled explicitly. On the other hand, phase-field models are extremely computationally intensive as they involve the solution of a non-convex optimization problem at each time step. Moreover, due to the discrete nature of lattice models and the smeared-out damage representation of cracks by the phase-field approach, it is not clear whether these methodologies will be able, without using prohibitive computing resources, to capture the complex multiscale behaviour characteristic of HF when multiple physical processes compete to determine their evolution. Thus no one computational method is currently able, without further development, to capture all the required physical processes. It is also timely for an update on recent laboratory experiments involving more complex hydraulic fracture situations such as the simultaneous propagation of multiple HF.

3 Presentation Highlights

Since many of the presentations have been recorded and posted online and all the abstracts are available online we will keep our description of the presentations brief. We have grouped the presentations into seven categories: Industry Perspective, Interaction between HF and natural fractures, Multiple Fracture Interaction, Numerical Techniques (including: DDM/BEM, DEM, XFEM, FEM, Phase Field), The Tip Region, Near-Surface Hydraulic Fractures, Miscellaneous. There were eight industry representatives who gave six talks, there were twenty faculty researchers from universities of whom nineteen gave presentations, and twelve students or postdoctoral fellows of whom eleven gave presentations. All the presentations were thirty minutes in duration including at least five minutes for questions and discussion.

Two presentations were singled out as highlights by the attendees : 1) the analysis by Egor Dontsov of the transition of closely-spaced HF from ‘pancake-shaped’ fractures propagating in the viscous regime to ‘Petal-shaped’ HF propagating in the toughness regime, 2) the 3D capture, vizualization by student Will Steinhardt, and mechanism analysis by Shmuel Rubinstein of the formation of fracture steps behind the hydraulic fracture fronts in hydrogels.

1. Industry Perspective:

    - Sau-Wai Wong : HF modeling and design - a perspective on how things have changed from conventional to unconventional reservoirs.
    - Alexei Savitski: Outstanding challenges in modeling HF in unconventionals: What we know and what we cannot do.

2. Interaction between HF and natural fractures

- Olga Kresse: A stacked height P3D fracture network model and a parallel planar algorithm for the accurate modeling of HF propagating in multiple layered materials.
- Wei Fu: Crossing criteria at interfaces: HF influenced by spatially varying natural fracture properties.
- Guanyi Lu: Subcritical crack growth and time dependent HF initiation and propagation.

3. Multiple Fracture Interaction
   - Andy Bunger: A Swarm Theory Framework for evaluating the suitability of models for predicting the simultaneous growth of multiple hydraulic fractures.
   - Delal Gunaydin: Laboratory experiments involving the simultaneous propagation of multiple hydraulic fractures.
   - Innokentiy Protasov: Simultaneous growth of multiple P3D HF

4. Numerical Techniques
   (a) Displacement Discontinuity (DDM)/Boundary Element Methods (BEM)
      - John Napier: An unstructured triangular mesh model
      - Egor Dontsov: FracOptima models demonstrating the transition for closely spaced HF from 'pancake-shaped' fractures propagating in the viscous regime to 'Petal-shaped' HF propagating in the toughness regime.
      - Anthony Peirce: The Implicit Level Set Method used in conjunction with the Extended Kalman Filter to monitor HF propagation using tiltmeter measurements.
      - Ali Rezaei: The fast multipole method used for the efficient modeling of HF propagation in a porous medium using the displacement discontinuity method.
      - Sergey Golovin: An efficient implementation of the Implicit Level Set Algorithm for modeling planar HF.
      - Denis Esipov: A direct boundary element simulator for 3D HF propagation.

   (b) Discrete Element Methods (DEM) - Lattice Models
      - Christine Detournay: Nano-scale experiments and upscaling - investigation of Kerogen's effect on hydraulic fracturing using XSite.

   (c) eXtended Finite Element Method (XFEM)
      - Thomas-Peter Fries: Explicit/implicit XFEM crack description for HF with emphasis on transport models on curved crack surfaces.
      - Robert Gracie: How to build a stable and efficient sequential coupling schemes for HF simulation.

   (d) Finite Element Method (FEM)
      - Adrian Lew: Description of a Universal Mesh scheme to perturb FEM meshes to achieve high order accuracy to model thermally and hydraulically driven fractures.
      - Sergey Golovin: Crack propagation in poroelastic medium

   (e) Phase Field
      - Mary Wheeler: Diffusive Fracture Network representations in tight formations.
      - Sanghyun Lee: Phase field modeling for fracture propagation in porous media.
      - Erwan Tanne: A variational phase field model of HF.
      - Keita Yoshioka: A phase field hydromechanical model of reservoir simulation.

5. The Tip Region and Regimes of Propagation
   - Alena Bessmertnykh: Herschel-Bulkley fluid and the representation of proppant packing by a stress jump.

- Fatima Moukhtari: A semi-infinite HF driven by a shear-thinning fluid.
- Gennady Mishuris: Analysis of the fluid-induced shear-stress at the tip at the HF tip.
- Will Steinhardt/Shmuel Rubinstein: Vizualization and instability at the HF front in hydrogels. The detailed investigation of the formation of 'fracture steps' behind the fracture front.
- Dmitry Garagash: Is Linear Elastic Fracture Mechanics (LEFM) justified in hydraulic fracturing?

6. Near-Surface Hydraulic Fractures

   - Thomasina Ball: Magma-driven, gravity/bending and viscosity/toughness
   - Zhiqiao Wang: Universal tip solution - viscosity/toughness

7. Miscellaneous

   - Nancy Chen: Net Present Value Analysis - optimization of well and fracture placement.
   - Robert Viesca: Fluid-induced Faulting: aseismic slip - two asymptotic regimes.
   - Peter Grassl: Multiple cracks from a pressurized spherical cavity.
   - Erfan Sarvaramini: A continuum approach for stimulated rock volume.
   - Emmanuel Detournay: HF in very permeable rocks.

4 Scientific Progress Made

In addition to a considerable exchange of new ideas this workshop has stimulated a number of planned collaborations among the participants (see comments below). A significant benefit from a workshop like this is the opportunity it provides for students and postdoctoral fellows to meet and learn from researchers whose papers they have only read. This educational opportunity also enables the students to gain perspective on how their research fits into the 'big picture' of research initiatives in the field.

This workshop has fostered the formation of an international team of researchers and practitioners interested in moving the field forward. There was discussion of biennial or triennial meetings in different parts of the world. Indeed, there was an offer by the delegates from Novosibirsk to host such a workshop in 2019 to interact with Russian researchers who have been actively engaged in HF research the past few years.

Below are just a selection of comments solicited from attendees:

Comment from an industry participant:

"It was one of the most effective workshops I had ever attended. The topics discussed range from hydraulic fracture practitioner perspectives to nitty gritty details of various numerical and analytical methods. Diversity in the talks was certainly the key in this successful event. Yet, each day had a clear theme and these presentations on a coherent theme kept the story flow very smoothly. Last not but least, spending consecutive 5 days in somewhat isolated location helped enhance our intimate discussions with other experts and scholars in the field."

Faculty member comments:

1. "The combination of industry and academia was outstanding. It was an academic conference, primarily, but the presence of an active minority from industry kept the discussions honest and ensured we did not stray from the application that provides the reason for working on these problems in the first place.

2. I walked away with tangible benefits that include plans for 2 papers to be co-authored with various cohorts of colleagues from the conference, and my students and I were made aware of and provided with basic training on a powerful package of freely available analysis software that we are starting to use already.

3. The amazing surroundings, healthy lifestyle, and complete freedom from the worries of life provided by the conference center and staff were conducive to my own reflection on research. On the flight home and in the days that followed I outlined proposals on 2 new topics related to hydraulic fracturing.

4. One of my students reflected that this is the first time she really understood where her work fits within the global research community, and knowing the place of the work completely changes her motivation and approach going forward.

5. All of my students were surprised to see how much fun scientists have when they get together to discuss, argue, discover, and encourage together."

Selection of student comments:

1. "Thank you for organizing such an amazing workshop. This workshop brings together people who are conducting cutting edge researches on hydraulic fracturing from all around the world. It also provides a great opportunity to students to learn the most up-to-date knowledge about experiments and modeling in hydraulic fracturing. I am glad to have attended this workshop and have benefited a lot from all the presentations."

2. "I learned from and enjoyed every moment of this excellent workshop. Both the venue and location of the workshop were amazing, but what made this workshop more exciting for me was to meet all the people that I knew by name from their papers and contributions in the hydraulic fracturing field. I think the material presented in the workshop was a thoughtful combination of mathematics, numerical models, and experimental work in the field of hydraulic fracturing. In this sense, the workshop was on top of the edge and being delivered by experts in the field."

3. "Thank you for the invitation to the HF workshop. It was an excellent week of talks. For myself as a PhD student, it was a great opportunity to chat with people in the field that I had read so much of the work of. In particular, talking to Emmanuel about our similar work on near-surface fractures. And also talking to Andy about some related solidification experiments that could be done to investigate magmatic intrusions (which excitingly I should be able to do soon!)."

5 Outcome of the Meeting

In response to the industry presentations and discussion participants agreed on the formation of a list of open problems/challenges that the newly-formed community can work on. It is anticipated that the various research groups will further develop the algorithms/techniques/experiments they are working on to try to address these problems. One exciting proposal among this list is the establishment of a modeling challenge that has come from practitioners in the field in which existing models fail to predict the outcome of an actual stimulation sequence. This challenge along with as much data as possible would be provided to participants a few months before the next workshop. As an extension of this idea, another participant proposed assembling an easily accessed data base of such modeling challenges.

List of Open Problems

1. The Sinkey Challenge: All future workshops should have a modelling challenge from industry that the modelers/analysts could try their codes/scalings on to see if they can explain the puzzling phenomenon. The proposers would preferably submit the description a while before with as much detail and data as possible.

2. Development of phenomenological models in HF similar to the diffuse damage models described by Mary Wheeler and Erfan Sarvaramini presented. Those models fit the present data which is scarce and the best we can hope for is: geological data, pump rates, mixtures, and finally, production rates. We have to work with this, and the hope for high-quality data in large quantities to verify regimes and influences from rheology, turbulence, etc.

3. Creation of a database of challenging HF stimulation cases from industry in which standard modeling failed to explain the phenomena observed. As much data as possible would be available to modelers in an easily accessible format.

4. The impact of material heterogeneity on hydraulic fracture predictions in physical and numerical settings. Heterogeneities could be at the grain scale (potentially impacting tip behavior), or at a larger, engineering scale.

5. Confirm the multiple crack results presented by a number of speakers in numerical and experimental studies.

6. Near wellbore issues. “Tortuosity” has been recognized for decades but very little is known about horizontal wells, and even for vertical wells there is no systematic theory for predicting, modeling, or deliberately modifying near wellbore tortuosity. Also, all models are static, while it is know that tortuosity is transient. This is a major area where little is known and industry believes is essential, perhaps more than any other single issue, to successful application.

7. Develop criteria to avoid the oscillation instabilities that arise in the modelling of simultaneously propagating, closely spaced, hydraulic fractures.

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