2018-2019 Grand Challenge Award – Final Report

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Research Award Title: A GFEM Framework for Reservoir Simulation of Unconventionals

Background

Projections through the year 2040 maintain that approximately 70% of domestic energy consumption will come from subsurface liquid and gas resources. Two thirds of the production of those resources will come from tight (low permeability) or "unconventional" subsurface formations [1], where reservoir fluids are extracted through complex hydraulically induced and/or natural fracture networks. These reservoirs yield low extraction efficiencies that are often less than 6%. While engineers have made improvements over the last decade through trial and error (which have generally led to increased water consumption), it is clear that a basic science gap stands in the way of further improvements that must be addressed to understand how and why enhanced recoveries are being realized.

The current generation of computational models and software commonly used to simulate subsurface fluid transport, while experiencing continuous upgrades in the flow physics (e.g. compositional mass balances, flash calculations, advanced constitutive models for relative permeability and capillary pressure), are little changed from a computational methods and software engineering standpoint from simulators developed 40 years ago. Additionally, if they include any effects from geomechanical deformation and/or failure processes at all, they are typically simplistic, loosely coupled, and implemented as an afterthought. These models are *entirely inadequate for understanding fluid flow in unconventional reservoirs* where fracture formation and aperture opening/closing governs the fluid dynamics in a strongly nonlinear way. Fluid flow in unconventional reservoirs is dominated by localized phenomena that occur in and around both natural and hydraulically stimulated fractures [2]; however, the current simulators and the computational methods they are based on lack the multiscale technology in the numerics to account for the complex physics near fine-scale fractures which govern the fluid transport over long distances on the scale of a subsurface reservoir. Larger computers, distributed memory parallelization, and more degrees of freedom, have been the primary tool for resolving heterogeneity; but that approach is hopeless where there are many orders of magnitude difference between the length scales that dominate the physics and the large length scales associated with the quantities of interest (e.g. liquid/gas production, water injection, surface seismicity and subsidence). New models which incorporate multiscale features into the numerical approximation, are fully coupled with sophisticated multiphysics (e.g. thermal, geomechanics), exploit the upcoming generation of exascale computers with their heterogeneous architecture and differing paradigms of parallelization in a performance portable way, and use agile software development strategies to allow for future improvements in physics and numerics, are crucial to enhance scientific understanding of unconventional reservoirs.

To address the shortcomings of the current models related to subsurface fluid flow in unconventional reservoirs, we proposed the following integrated research goals:

1. Development of a generalized finite element method, based on partition-of-unity concepts [3], that can embed multiscale physics and heterogeneous physical properties into the approximation spaces of the numerical discretizations for coupled subsurface fluid flow and deformation mechanics.
2. Agile software development, building from the DOE open source framework Trilinos, that facilitates arbitrary partition-of-unity approximation spaces and performance portable algorithms targeting heterogeneous architectures and exascale high-performance computers.

The **impact** of the proposed research will be an improved understanding of fluid flow in unconventional reservoirs that will provide for *improved predictions, physical insight, and decision making for regulatory measures, environmental impact, and resource and water stewardship.* Additionally, the newly developed models will be applicable outside of unconventional reservoirs, e.g. in enhanced geothermal energy applications, contaminant transport in fractured aquifers.

Preliminary Results - Buckely Leverett Problem

To demonstrate the ideas pursued during the project, we will use as a model problem the so-called "Buckely-Leverett problem". The mathematical formulation is derived from writing mass balance equations for multiphase fluid flow in a porous media containing oil and water. After several assumptions regarding the constitutive behavior of the fluids which include assumptions of incompressibility, no capillary pressure, etc. the final mathematical form can be written as

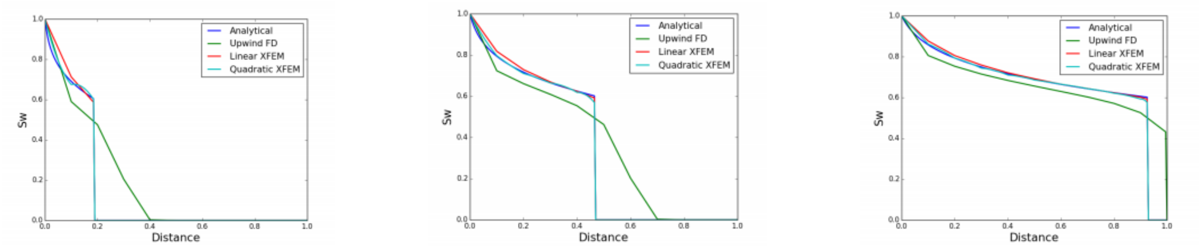
$$\phi \frac{\partial S_w}{\partial t} = -\frac{q_t}{A} \frac{\mathrm{d}f_w}{\mathrm{d}S_w} \frac{\partial S_w}{\partial x} \tag{1}$$

where ϕ is the porosity, $S_w = S_w(x,t)$ is water saturation, q_t is the volumetric injection rate of water, A is the cross-sectional area, with

$$f_w = \frac{k_{rw}(S_w)\mu_o}{k_{rw}(S_w)\mu_o + k_o(1-S_w)\mu_w} \tag{2}$$

where k_r is relative permeability, μ is fluid viscosity, and the subscripts *o, w* indicate oil and water respectively. This equation has a semi-analytical solution which develops a "shock" or discontinuous S_W at the displacement front where the water initially contacts the oil in space.

The Buckley-Leverett problem is the classical first- choice verification problem used in evaluation of numerical schemes for multiphase flow in petroleum engineering applications. Using this equation we formulated a generalized finite element method (GFEM) [3] where the FEM shape functions are enriched with discontinuous functions. Preliminary results of these simulations compare the GFEM solutions to the semi-anlytical solution and the standard upwinded finite difference solutions as shown in Figure 1.



(a) Early time saturation profile (b) Middle time saturation profile (c) Late time saturation profile

Figure 1: GFEM Buckley-Leverett Solution Comparison.

It was shown that the GFEM solution can outperform the standard finite difference techniques with respect to accuracy even with a minimal number of degrees-of-freedom. This research has led to the significant research products still in development outlined in the following section.

Research Products

The preliminary results of the Moncrief Grand Challenge Award contributed to the preparation of the following proposal which was funded.

- External Funding: “Assessing Capillary End Effects on Large Scale Tight Reservoir Drainage.” The ACS Petroleum Research Fund, American Chemical Society. October 2020. $110,000

Additionally, a journal article manuscript describing the GFEM formulation is being prepared for submission to Computer Methods in Applied Mechanics and Engineering. Other articles that were worked on and published during the Moncrief Grand Challenge Award and related to the proposed work are

- Y. Leng, X. Tian, and J.T. Foster. *Super-convergence of reproducing kernel approximation. Computer Methods* in Applied Mechanics and Engineering, 352:488–507, August 2019. doi:10.1016/j.cma.2019.04.038.

Finally, the source code for the code being developed is available open source at https://github.com/johntfoster/puffrs

References

[1] U.S. Energy Information Administration**, Annual Energy Outlook 2017 With Projections to 2050, electronic, www.eia.com/aeo, 2017.**

[2] B. Berkowitz, *Advances in water resources* **25,** 861 (2002).

[3] C. A. Duarte**,** I. Babuska, and J. T. Oden**,** *Computers & Structures* **77**, 215 (2000)**.**