INL/CON-21-63635-Revision-0

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-EE0007080

A Mixed Fracture-Matrix Model for Evaluating Well Orientation and Completion Options for the Utah FORGE Site

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Keywords

Discrete fracture network, FORGE, MOOSE

ABSTRACT

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Title: A Mixed Fracture-Matrix Model for Evaluating Well Orientation and Completion Options for the Utah FORGE Site
Abstract: Orientation and completion for well pairs that have been subjected to multi-zonal stimulation play a critical role in the long-term performance of an Enhanced Geothermal Reservoir. Here we present the development of a methodology to rapidly and efficiently numerically simulate mixed fracture-matrix flow systems for evaluation of well design and completion options. An example evaluation based on a small fracture network representative of FORGE Well 16(A and B)-78(32) follows a discussion of the theory and model validation.

1. Introduction

Predictive simulations involving fractured porous media requires an accurate representation of the discrete fracture network (DFN) and its role in physical phenomena related to flow and transport. Predictive simulations using computational methods like the finite element method require the geometry to be discretized into elements of a mesh. Ideally, all the DFN's complex geometric features must be captured by the mesh. Creating a 3D mesh containing a 2D or 3D representation of the DFN is difficult. For this reason, we develop a modeling methodology in which the fractured porous media is decomposed into two separate domains – one representing the DFN network and the other containing the surrounding porous matrix – and loosely couple these two domains by exchanging heat energy. This simplifies our workflow by allowing us to produce a mesh of the matrix material completely independent from the mesh of the DFN.

Although the main goal of this loose coupling strategy is to simplify the meshing process, we also expect decreases in computational costs for the following reasons. (1) This simplification in the mesh reduces the number of volumetric elements in the matrix material leading to a smaller computational cost. (2) The computational cost is further reduced by separating the "faster" physics of porous flow in the fracture network from the "slower" diffusion in the matrix, allowing us to use different timestep sizes on each domain. (3) The separation of fast and slow physics also leads to a better conditioned linear system, further reducing the computational

overhead. On the other hand, the loose coupling breaks the unconditional stability of a fully-implicit, fully-coupled solve.

In the sections that follow, we provide an overview of the loose coupling methodology as implemented in the MOOSE (Multiphysics Object-Oriented Simulation Environment) framework [Permann et al. (2020)]. We then present an example.

2. Loose Coupling Algorithm

For many years, researchers in various fields have loosely coupled different codes together to achieve goals similar to ours. Conceptually, our methodology is no different than these traditional approaches, but utilizing the MOOSE framework offers many advantages, as outlined below.

The MOOSE framework encapsulates the complexities of writing high performance computational software (e.g. parallel communication, numerical discretization, and nonlinear solvers) allowing a computational scientist to only focus on implementing and solving the differential equations governing the physics of interest. Several sets of differential equations governing different types of physics have been implemented as modules in MOOSE (e.g., diffusion, radiation transport, mechanics). In our work we use the PorousFlow module [Wilkins et al. (2020), Wilkins et al. (2021)] allowing us to capture the physics governing fluid and heat flow in porous media. Our loose coupling methodology is based on the MOOSE MultiApp system [Gaston et al. (2015)], which provides us with the ability to control the execution/time-stepping of multiple computational domains and the data transferred between them. Unlike many previous code-coupling schemes, MOOSE's MultiApp system is well-established and rigorously tested.

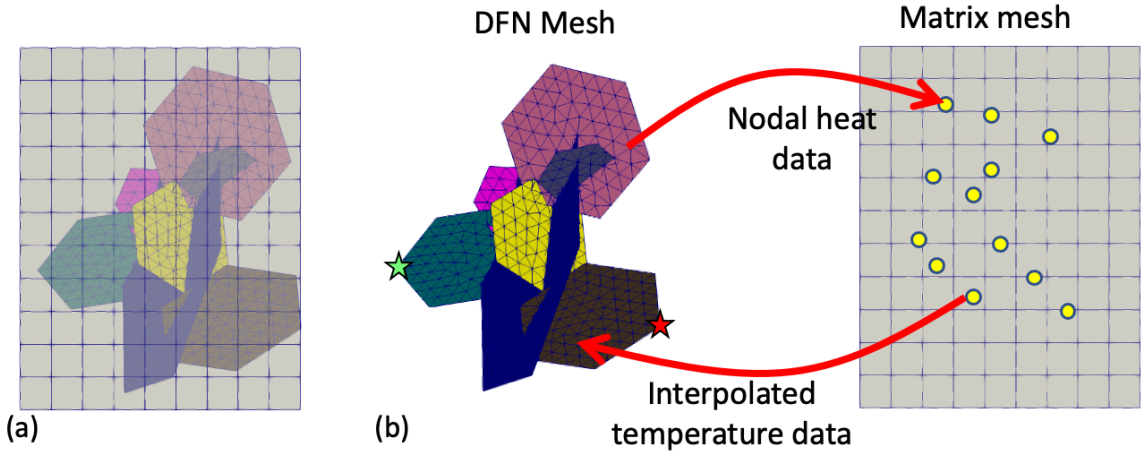

Figure 1: (a) The 2D DFN sits within the volumetric domain of the 3D porous matrix, but the meshes do not conform. (b) illustrates the separate computational domains and the loose coupling. The green and red stars indicate the injection and production points of the example, below.

The starting point of our loose coupling methodology is that the fractures can be considered as lower dimensional entities within the higher-dimensional porous media, such as illustrated in Figure 1(a). (A consequence of our proposed methodology is that fractures do not provide a barrier to flow in their normal direction.) The two computational domains are governed by coupled thermo-hydraulics physics, where the heat equation describes heat conduction and convection, and Darcy's equations describes fully saturated porous flow. The two domains

transfer heat information as shown in Figure 1b.

Briefly, the coupling algorithm proceeds as follows.

1. At the start of a timestep, the matrix mesh passes its temperature field, T_m, from the previous timestep to the DFN. The DFN interpolates T_m to every node in the DFN.
2. The DFN simulation then computes a fracture pore pressure and temperature field, T_f. according to the thermo-hydraulic physics along with a heat-transfer rate to the matrix:

$$Q = h(T_f - T) \tag{1}$$

   where h is the heat-transfer coefficient. The heat transfer coefficient is given by

$$h = 2\,\lambda/L \tag{2}$$

   which includes the effect of the matrix element length, L, on the heat transferred to between the matrix and fracture, and the λ is the matrix thermal conductivity in the direction normal to the fracture. This equation is derived assuming close-to steady-state heat flows have been achieved between the fracture and the nearest matrix nodes, so is inappropriate if short-time, small-scale phenomena are of interest. This is quantified below.

3. The matrix simulation applies Q as a point heat source, and using its thermo-hydraulic physics, computes a new matrix pore pressure and temperature field, T_m.
4. This completes the current timestep and the process repeats from step 1.

In this process, the matrix temperature transferred to the fracture is held fixed for each timestep taken in the fracture simulation. The opposite is also true: the heat source from the fracture simulation is held fixed during the matrix simulation timestep. This fixing means that large quantities of heat can be transferred back forth between the matrix and fracture in a single timestep, leading to an unphysical oscillatory behavior in the solution. These issues would not occur in a fully-coupled, conformally meshed DFN-matrix. All of the steps described in the loose coupling algorithm are controlled by the MOOSE MultiApp system.

3. Example DFN Simulation

The above loose coupling methodology is applied to a small DFN representative of FORGE Well 16(A and B)-78(32) [Finnila et al. (2021)], shown in Figure 1. In this analysis, we assume the following:

- the physics is fully-saturated, non-isothermal porous flow with heat conduction and convection;
- the water properties in both the fracture and the porous material are described by the IAPWS (2008, 2014) water equation of state;
- the pore pressure is initially hydrostatic, around 10MPa corresponding to a depth of around 1km;
- the temperature is 200^{o}C;
- injection is into the fracture network only, through the one point shown as a green star in Figure 1, at a rate of 10kg.s^{-1} and temperature of 100^{o}C;

- production is from the fracture network only, through the one point shown as a red star in Figure 1, at a rate of approximately 10kg.s^{-1} (it cannot be exactly 10kg.s^{-1} initially because this causes large pore pressure reductions due to thermal contraction of water and because the aperture increases in response to the injection);
- the fracture aperture dilates elastically in response to enhanced pore pressure;
- only heat energy is transferred between the fracture and the matrix: the matrix heats the cool water injected into the fracture network.

3.1 DFN simulation

The DFN contains 12 individual fractures shown in Figure 1 that range in size from 40-150m, meshed with three-noded triangular elements. The initial fracture aperture is assumed to be a_o=0.1mm for all fracture planes. The fractures are assumed to dilate due to increasing pore pressure by

$$a=a_o+A(P-P_o) \tag{3}$$

where A= 10^{-3} m.MPa^{-1} (a pressure increase of 1MPa dilates the fracture by 1mm) and P_0 is the hydrostatic insitu value of around 10MPa . The permeability of the fracture is proportional to a^2, with insitu permeability of 10^{-11} m^2 when $a=a_0$.

3.2 Matrix Simulation

The matrix computational domain measures 220m x 170m x 220m, and discretized by a structural mesh of eight-noded hexahedral elements. The physics models and material properties used to model the matrix material are more straightforward as they do not contain any information about the DFN or fracture aperture. It is assumed the rock matrix has small porosity of 0.1 and permeability of 10^{-18} m^2. The rock density is 2700kg.m^{-3} with specific heat capacity of 800J.kg^{-1}.K^{-1} and isotropic thermal conductivity of 5W.m^{-1}.K^{-1}.

3.3 DFN-Matrix coupling

Equation (2) for the heat transfer coefficient used to compute the heat rate between the matrix and fracture is only justified if the matrix element sizes are small enough to resolve the physics of interest. The time taken for a pulse of heat to travel through the matrix over half-element distance L is

$$t\sim c\rho\lambda^{-1}L^2 \tag{4}$$

This equation provides an estimate of the element size needed to accurately resolve physical phenomena. The matrix simulations in this example use elements sizes of 20, 10, and 5 m which produce simulation time-scales of 500, 125 and 5 days, respectively. If the simulation time is smaller than these enumerated time-scales, then Equation (2) is inappropriate and the simulation is likely to be inaccurate. To combat this, the matrix mesh should be made finer, or another form for heat transfer coefficient chosen.

3.4 Coupled DFN-Matrix Simulation Results

Figure 2 (a) and (b) show the temperature at the production bore. It is clear that the matrix provides substantial heat-energy to the injectate. However, as time proceeds, the cold injectate cools the surrounding matrix, leading to cooler production temperatures. These figures show how

the results depend on the matrix and fracture mesh sizes. Keep in mind the Equation (4), which estimates the time scale at which the results should become accurate (eg, the "20m, 9.2m" case is not expected to be accurate for time-scales less than about 500 days).

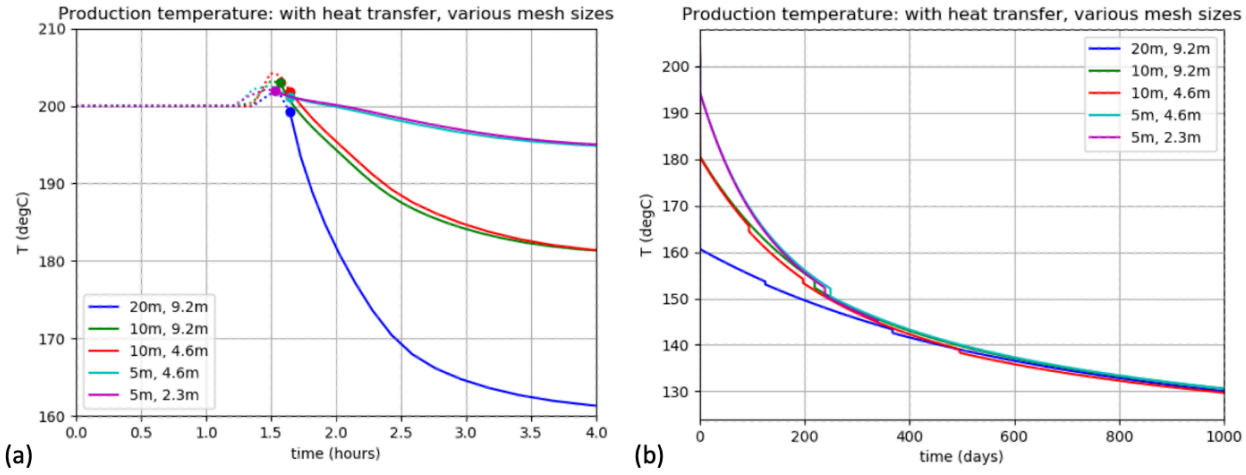

Figure 2: (a) Short term and (b) long term well production temperatures for the loosely coupled DFN-Matrix simulations. The first number in the legend is the mesh element size, while the second is the fracture element size.

Figure 3 shows the evolution of fracture aperture, which dilates from 0.1mm to around 3mm in this simulation.

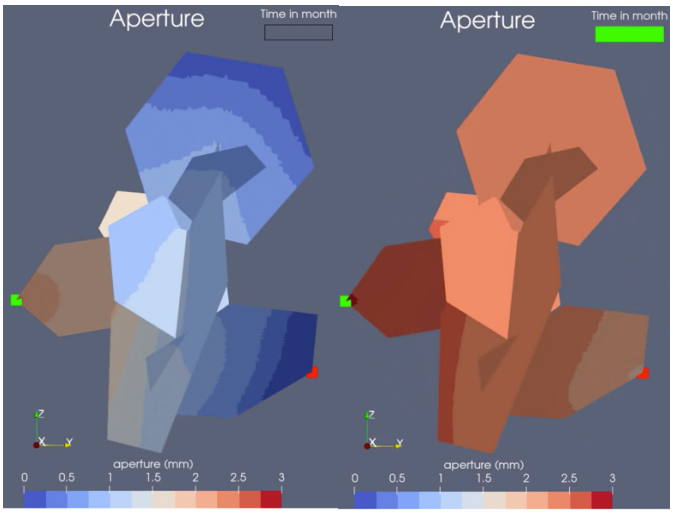

Figure 3: Fracture aperture. (a) a few hours after injection commences. (b) after 1 month of injection.

Figure 4 shows the evolution of the cooled matrix material. By 1000 days, an envelope of 10–20m around the fracture system has cooled by more than 10°C. Some parts of the fracture are not cooled at all by the injectate, most particularly those at the top of the network, where hot, buoyant water tends to reside.

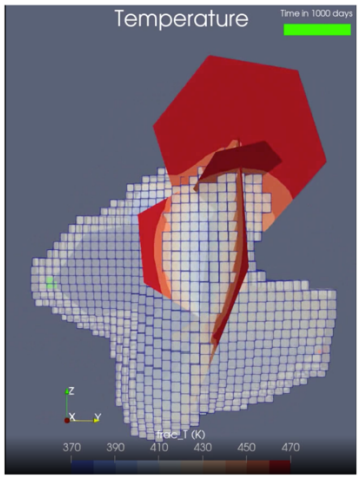

Figure 4: Cooled matrix material after 1000 days. Colors on the fracture system show fracture temperature. The small boxes are matrix elements that have cooled by more than 10°C.

4. Conclusion

In this work we presented a loosely coupled DFN simulation methodology that will greatly improve our workflow used to evaluate the performance of enhanced geothermal reservoirs. This loosely coupled protocol allows us to model the DFN separate from the matrix. This separation of computational domains allows us to mesh each feature separately, simplifying the meshing of DFN's as two-dimensional planes that do not need to be incorporated into the three-dimensional volumetric mesh of the matrix. We expect this framework to provide additional computational savings by simplifying the physics of each computational domain. We applied the loosely coupled simulation protocol to small DFN containing 12 fractures to capture the temperature change across the DFN between an injection and production borehole. Future work will enhance the current set of simulations to include more fractures in the DFN, material properties representative of the FORGE site, and other methods of including fracture aperture changes as the model evolves.

Acknowledgement

Funding for this work was provided by the U.S. DOE under grant DE-EE0007080 "Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site". We thank the many stakeholders who are supporting this project, including Smithfield, Utah School and Institutional Trust Lands Administration, and Beaver County as well as the Utah Governor's Office of Energy Development.

This research made use of the resources of the High Performance Computing Center at Idaho National Laboratory, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517.

REFERENCES

Permann, C.J., Gaston, D.R., Andrš, D., Carlsen, R.W., Kong, F., Lindsay, A.D., Miller, J.M., Peterson, J.W., Slaughter, A.E., Stogner, R.H. and Martineau, R.C., 2020. MOOSE: Enabling massively parallel multiphysics simulation. *SoftwareX*, 11, p.100430.

Gaston, D.R., Permann, C.J., Peterson, J.W., Slaughter, A.E., Andrš, D., Wang, Y., Short, M.P., Perez, D.M., Tonks, M.R., Ortensi, J. and Zou, L., 2015. Physics-based multiscale coupling for full core nuclear reactor simulation. *Annals of Nuclear Energy*, 84, pp.45-54.

IAPWS (2008). Release on the IAPWS Formulation 2008 for the Viscosity of Ordinary Water Substance. Technical Report, IAPWS, 2008. URL: www.iapws.org/relguide/visc.pdf

IAPWS (2014). Revised Supplementary Release on Backward Equations for Specific Volume as a Function of Pressure and Temperature v(p,T) for Region 3 of the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam. Technical Report, IAPWS, 2014. URL: www.iapws.org/relguide/Supp-VPT3-2016.pdf

Wilkins, A., Green, C.P. and Ennis-King, J., 2020. PorousFlow: a multiphysics simulation code for coupled problems in porous media. Journal of Open Source Software, 5(55), p.2176.

Wilkins, A., Green, C.P. and Ennis-King, J., 2021. An open-source multiphysics simulation code for coupled problems in porous media. Computers & Geosciences, 154, p.104820.

Finnila, A., Doe, T., Podgorney, R. Damjanac, B. and Xing, P., 2021. Revisions to the Discrete Fracture Network Model at Utah FORGE Site. *GRC Transactions*, 45