Can Coupled Geomechanics Improve Forecasting in Enhanced Geothermal Systems?

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ABSTRACT

Thermo-hydraulic modeling of fluid flow and heat extraction in porous media is widely used in enhanced geothermal systems (EGS), often incorporating discrete fracture networks to represent complex fracture geometries. In these models, the elevated permeability near fractures is typically governed by aperture width—a key parameter for matching field observations. However, many existing approaches do not fully couple fracture opening and closure with mechanical responses to high-pressure fluid injection, potentially limiting their predictive accuracy. To address this, we focus on a single dominant fracture at the Utah FORGE site and develop a coupled thermo-hydro-mechanical (THM) model using a discontinuous Galerkin method integrated with a cohesive zone model to explicitly capture fracture deformation during injection. This formulation allows fracture aperture to evolve dynamically in response to thermal stresses and fluid pressure, enabling more realistic predictions of permeability evolution. By reducing the computational domain to a few hundred meters and focusing on a single fracture, we strike a balance between physical fidelity and computational feasibility. The model is further coupled with an optimization algorithm to calibrate key parameters against observed data. We compare the results with those from a purely thermo-hydraulic model using a prescribed aperture distribution—such as an elliptical profile with sigmoid decay—to evaluate whether geomechanical coupling improves predictive performance. The findings provide insights into the role of mechanical feedback in EGS performance and offer a valuable tool for the design and optimization of stimulate strategies.

1. INTRODUCTION

Physics-based modeling of fluid flow and thermal transport in porous media is fundamental for understanding and optimizing enhanced geothermal systems (EGS). These models are widely used to predict heat extraction and reservoir performance, often incorporating discrete fracture networks (DFNs) to represent the complex geometry of fractures that dominate fluid circulation. However, most existing approaches primarily focus on thermo-hydraulic (TH) processes and neglect geomechanical effects due to the significant computational cost and numerical challenges associated with fully coupled simulations. This omission is critical because mechanical feedback governs key phenomena such as fracture initiation and propagation, aperture evolution, induced seismicity, and surface deformation—all of which strongly influence permeability and long-term energy recovery.

In conventional TH models, fracture permeability is typically assumed to be elevated relative to the surrounding rock and is often parameterized by fracture aperture width. Aperture is a key control on fluid flow and heat transfer, and its accurate representation is essential for matching field observations. Yet, many models adopt a constant aperture or impose an arbitrary spatial distribution, such as elliptical or sigmoid profiles, without accounting for the underlying physics. In reality, aperture evolution is driven by multiphysics interactions, including thermal stresses, fluid pressure, and rock deformation, and may also involve chemical effects. Ignoring these couplings can lead to unrealistic predictions and increased uncertainty in stimulation design.

Recent studies have demonstrated that incorporating thermo-hydro-mechanical (THM) coupling significantly improves the predictive capability of geothermal reservoir models. For example, Zhou et al. (2021) showed that mechanical deformation strongly affects reservoir pressure and heat recovery, while McLean et al. (2024) highlighted the role of stress-dependent aperture evolution in improving permeability forecasts. Despite these advances, practical implementation remains challenging due to computational complexity and the need for robust numerical formulations.

In this study, we aim to bridge this gap by developing a simplified yet physically consistent THM model focused on a single dominant fracture at the Utah FORGE site. Our approach employs a discontinuous Galerkin method integrated with a cohesive zone model (CZM) to explicitly capture fracture deformation under thermal and hydraulic loading. This formulation allows fracture aperture to evolve dynamically in response to fluid pressure and thermal stresses, providing a more realistic representation of permeability changes during injection and production. By restricting the computational domain to a few hundred meters and considering one injection and one production well, we achieve a balance between physical fidelity and computational feasibility. The model is calibrated against observed data and benchmarked against a conventional TH model with prescribed aperture profiles to assess the benefits of geomechanical coupling.

The results offer insights into the spatial and temporal evolution of fracture aperture, the influence of injection parameters on fracture geometry, and the implications for heat extraction efficiency. Ultimately, this work underscores the importance of mechanical feedback in EGS modeling and provides a foundation for integrating advanced multiphysics approaches into stimulation design and optimization workflows.

2. METHODS

The numerical modeling of thermos-hydro-mechanical coupling of geothermal systems is performed using the finite element (FE) application ELK (Electrical fracKing), which is built on the open-source MOOSE (Multiphysics Objected-Oriented Simulation Environment) framework (Lindsay et al. 2022). The thermo-hydro components leverage the Porous Flow module in MOOSE, while the mechanical behavior is modeled using the Solid Mechanics module. Fracture representation is achieved through a modified incomplete interior penalty Galerkin (IIPG) method (Liu et al. 2023), implemented as discontinuous Galerkin (DG) interface kernels. To capture fracture initiation and propagation, we apply a linear extrinsic/intrinsic cohesive law within the DG framework, enabling explicit modeling of fracture opening and closure under coupled thermal and hydraulic loading.

The hydraulic fracturing implementation follows the approach described in Liu et al. (2020), Yang et al. (2025) and Jin et al. (2025), which is omitted here for brevity. This integrated formulation allows fracture aperture to evolve dynamically in response to fluid pressure and thermal stresses, providing a physically consistent representation of permeability changes during injection and production.

3. RESULTS

3.1 Plane-strain KGD model

The MOOSE-based application ELK is extended to incorporate a bilinear intrinsic traction-separation law, as illustrated in Figure 1(a), which governs fracture initiation and propagation. To verify this implementation, we first performed a bar extension test using the existing extrinsic traction-separation law shown in Figure 1(b) and compared the simulation results with the analytical solutions, as shown in Figure 1(c), confirming consistency.
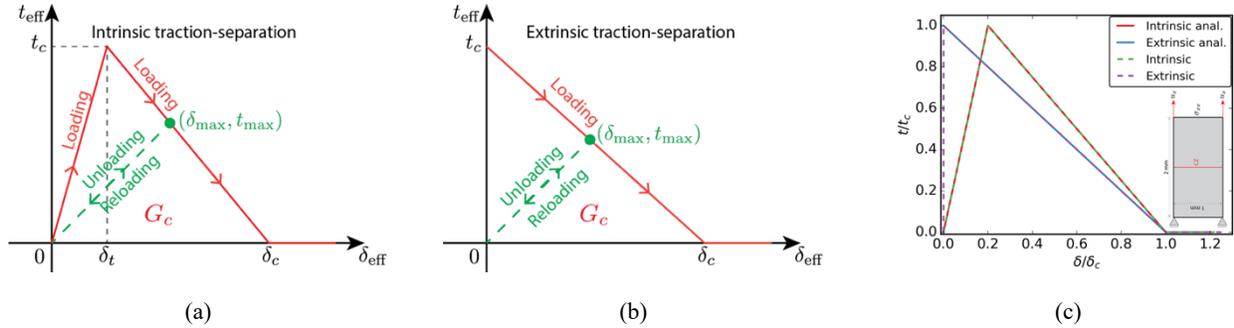

(a)   (b)   (c)

Figure 1: Schematics for (a) intrinsic and (b) extrinsic traction-separation laws, (c) Implementation verification by modeling a bar extension test.

Next, we investigated the influence of different traction-separation laws on hydraulic fracture initiation and propagation using the KGD benchmark model. The model setup follows Gao and Ghassemi (2020), as shown in Figure 2(a). There are two sets of model parameters, representing viscosity- and toughness-dominated regimes. These regimes are primarily governed by fluid viscosity and the fracture strength defined by the traction-separation laws. In our simulations, we used the same fracture energy density G_c (i.e., the area under the traction-separation curve shown in Figure 1) for both intrinsic and extrinsic laws to ensure a consistent energy basis for comparison.

The simulation results, presented in Figure 2, show that the type of traction-separation law has negligible impact on the viscosity-dominated regime. However, in the toughness-dominated regime, noticeable differences emerge during the early stages of fracture development, though these differences diminish as the fracture evolves. Some discrepancies between our results and those reported by Gao and Ghassemi (2020) were observed. We are currently investigating these differences and will provide further analysis next.

3.2 Radial hydraulic fracture model

To examine the evolution of aperture width during injection and production in a geothermal setting, we implemented a simplified radial hydraulic fracture model, as shown in Figure 3(a). The computational domain measures 20 m × 30 m × 30 m, with a vertical interface introduced as the potential fracture plane. Injection and production points are located at (0, -5 m, 0) and (0, 5 m, 0), respectively. The injection rate is set to 5 kg/s while the production rate starts at 80 seconds, linearly increases to 4.5 kg/s at 100 seconds, and remains 4.5 kg/s.

Fracture initiation is controlled by the fracture strength parameter in the cohesive zone model. To facilitate fracture development near the wellbore, this parameter is assigned a very low value (1E-6 MPa) within a circular region centered at the origin with a radius of 10 m. Outside this region, the fracture strength is set to 0.625 MPa, creating a contrast that influences fracture growth.

Figures 3(b) and 3(c) show the evolution of pore pressure and aperture width at the injection and production points. Over time, the values at production point approach those at injection points, suggesting progressive hydraulic conductivity. A longer simulation is required to assess whether a steady-state response is achieved.

Figure 4 illustrates the spatial distribution of pore pressure and aperture width at the time of 10, 500, and 1000 seconds. Initially, the fracture expands radially within the low-strength zone, forming a near-circular shape. Around 500 s, pore fluid reaches the production point, and by the end of the simulation, the aperture distribution remains approximately circular. Figure 5 shows the evolution of pore

pressure and aperture width along the line connecting the injection and production points. At steady state, the maximum aperture does not occur at the injection point, but closer to the center of the fracture. This indicates that aperture evolution is controlled not only by local pressure, but also by geometry, boundary conditions, and stress redistribution. Understanding these effects is critical for improving geothermal forecasting.
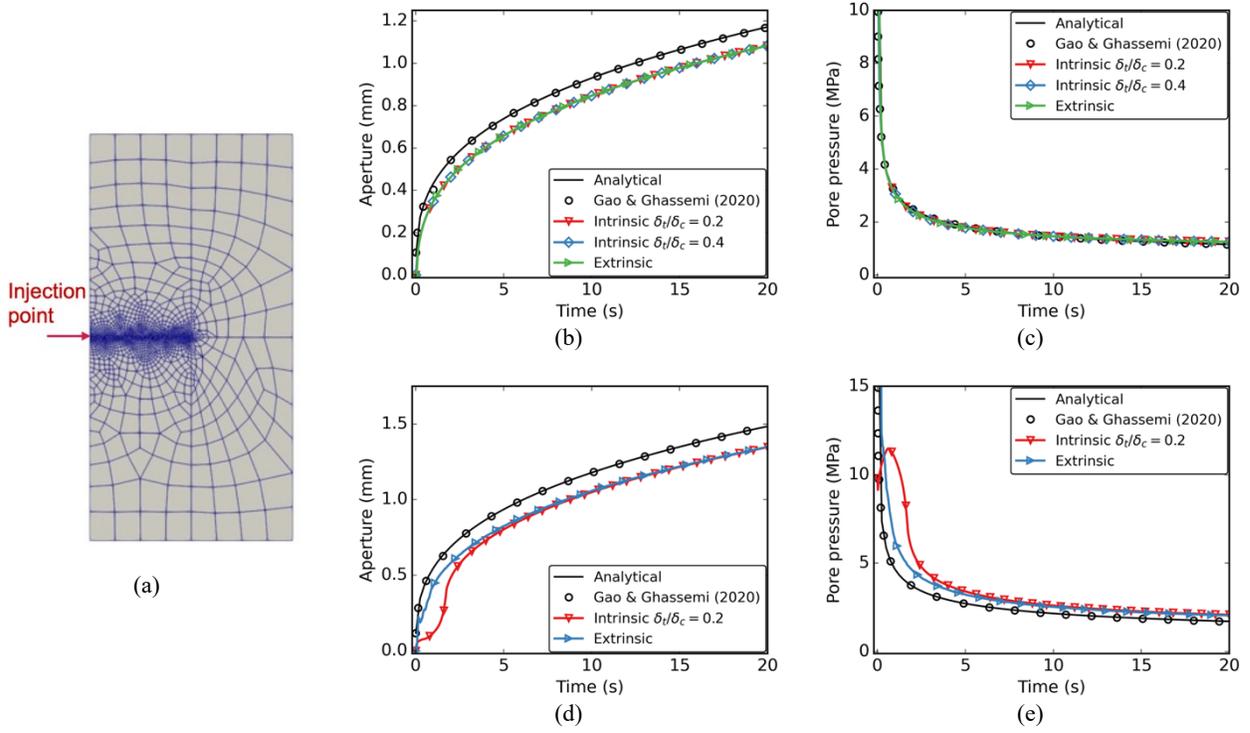

Figure 2: (a) KGD model setup, and evolutions of (b) (d) aperture width and pore pressure (c)(e) at the injection point for (b)(c) viscosity- and (d)(e) toughness-dominated regimes.
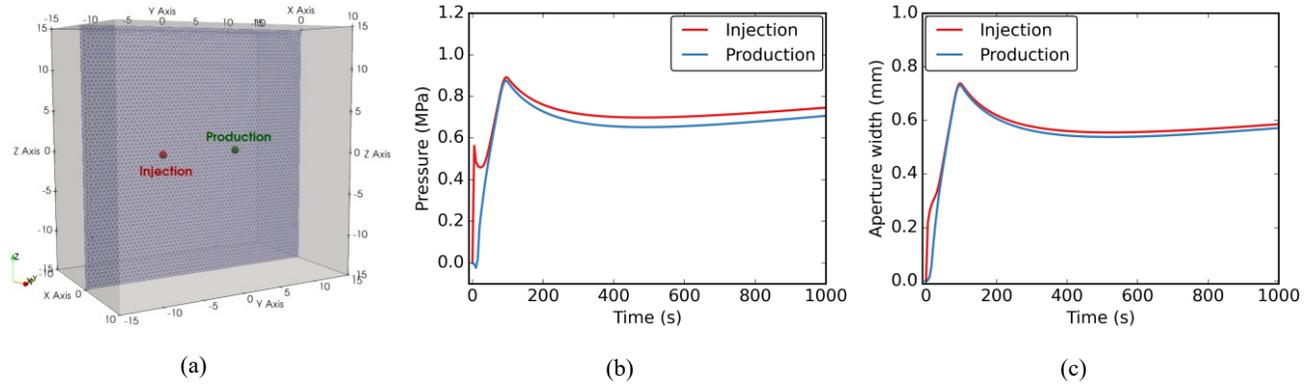

Figure 3: (a) Setup of the radial hydraulic fracture model with injection and production points and evolution of (b) pore pressure and (c) aperture width at injection and production points.
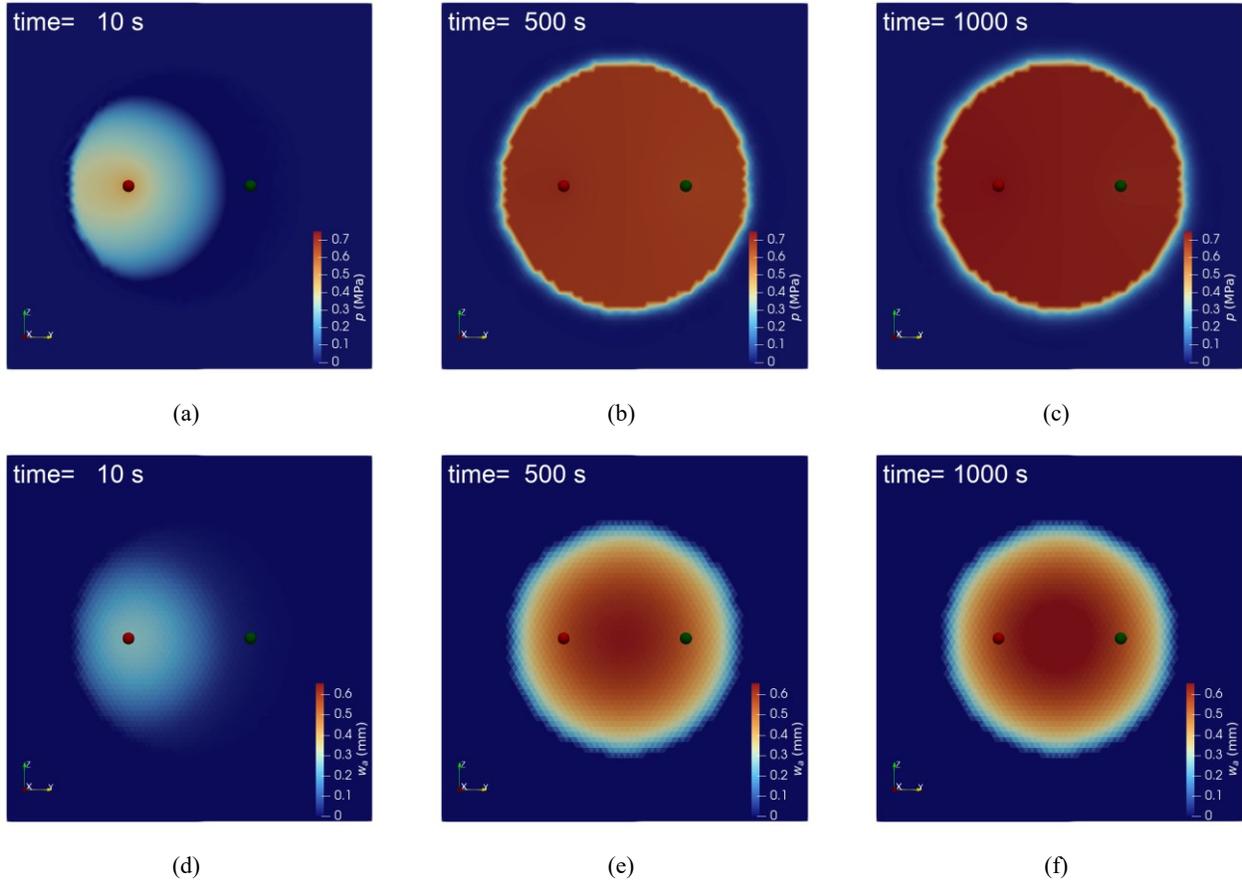
Figure 4: Distributions of pore pressure (top) and aperture width (bottom) at the time of (a)(d) 10 seconds, (b)(e) 500 seconds, and (c)(f) 1000 seconds.
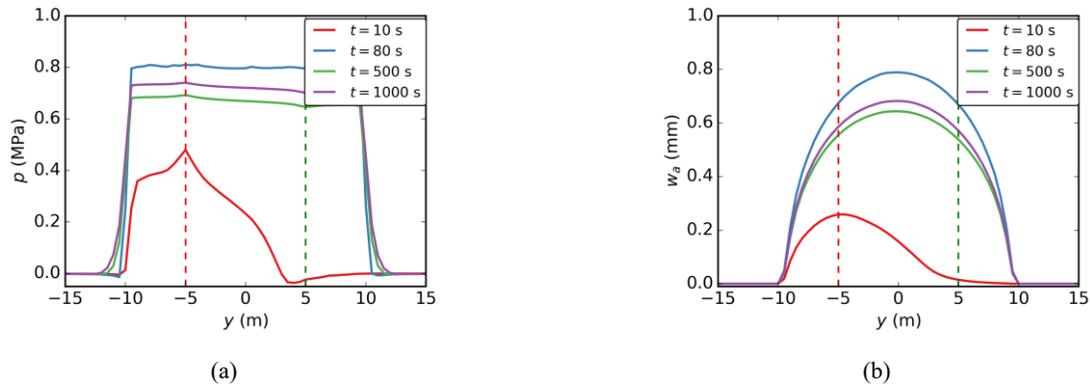

Figure 5: Distributions of (a) pore pressure and (b) aperture width along the line connecting the injection and production points.

4. CONCLUSIONS

We developed a coupled thermo-hydro-mechanical (THM) model using the MOOSE-based ELK application to simulate fracture initiation, propagation, and aperture evolution in EGS. Verification with KGD benchmarks showed that traction–separation laws have little effect in viscosity-dominated regimes but influence early fracture growth in toughness-dominated cases. A radial fracture model demonstrated that aperture evolves toward a circular pattern and hydraulic connectivity between wells, highlighting the role of geomechanical feedback in permeability prediction. These results confirm that THM coupling improves physical realism and can guide stimulation design and optimization for geothermal systems. Ultimately, mechanics-informed aperture distributions can be used to enrich TH models and improve geothermal forecasts at a manageable computational cost.

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