Multiscale Modeling Of Pressure-Driven Processes In Large Fracture-Based Energy Storage Systems

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Abstract

This study presents a model for simulating a subsurface pumped-hydro energy storage (battery) system. The model captures the coupling between fluid flow in an oil and gas type wellbore connected to a large hydraulic fracture embedded in a low-permeability reservoir. By integrating wellbore transport dynamics with fracture geomechanics, this work provides a robust framework for evaluating the performance of subsurface systems where pressure-driven energy storage mechanisms are dominant.

The model is implemented in COMSOL Multiphysics using coupled physics domains with independently structured meshes to address differing spatial and physical scales. Fluid flow in the 2D circular Penny-shaped fracture domain is governed by Darcy's Law and resolved with a fine mesh to capture steep pressure gradients, while the surrounding 3D reservoir is modeled using solid mechanics with a coarser mesh to capture deformation and stress redistribution. These domains are coupled through interface conditions that enforce mass and energy continuity, enabling simultaneous solution. Storage metrics including capacity, duration, power output, and round-trip efficiency are evaluated through parameter sweeps on fracture aperture and pressure conditions. Boundary conditions incorporate hydrostatic gradients and frictional losses to represent source point behavior through analytical formulations.

The results characterize system behavior across a range of operating scenarios and provide a basis for evaluating design tradeoffs in subsurface energy storage configurations. This computational framework demonstrates the viability of multi-physics approaches for complex geomechanical energy storage applications.

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Figures used in the abstract

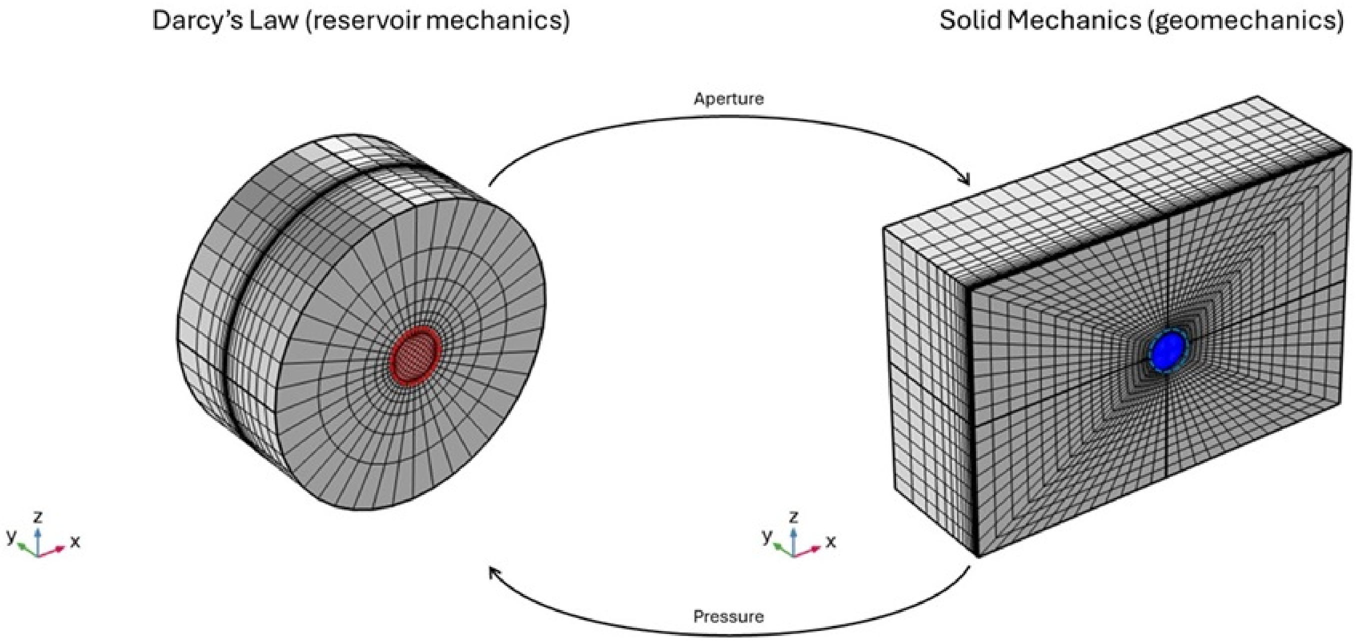

Figure 1 : Figure 1: Multiscale COMSOL model with separate meshes. Darcy domain (left) uses fine radial mesh for fluid transport; solid mechanics (right) uses coarse 3D mesh for rock deformation. Interface coupling maps fracture geometry with continuity conditions.

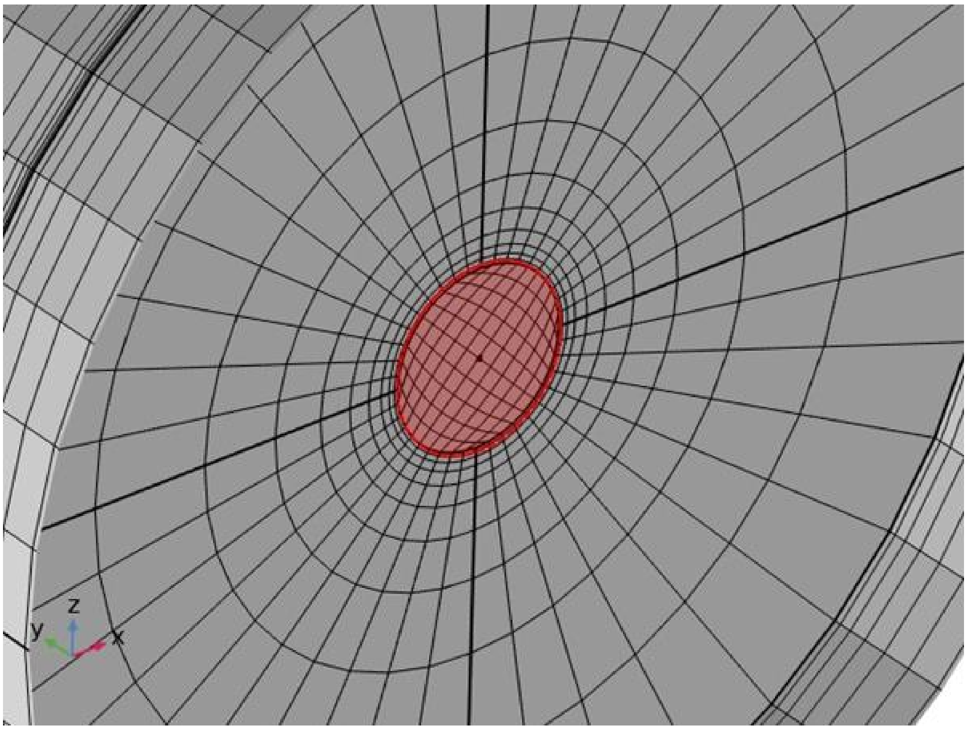

Figure 2 : Figure 2: Cross-sectional view of 2D fracture domain (highlighted) with radial mesh refinement. Darcy's Law governs fluid transport with high-resolution discretization near wellbore connection point.

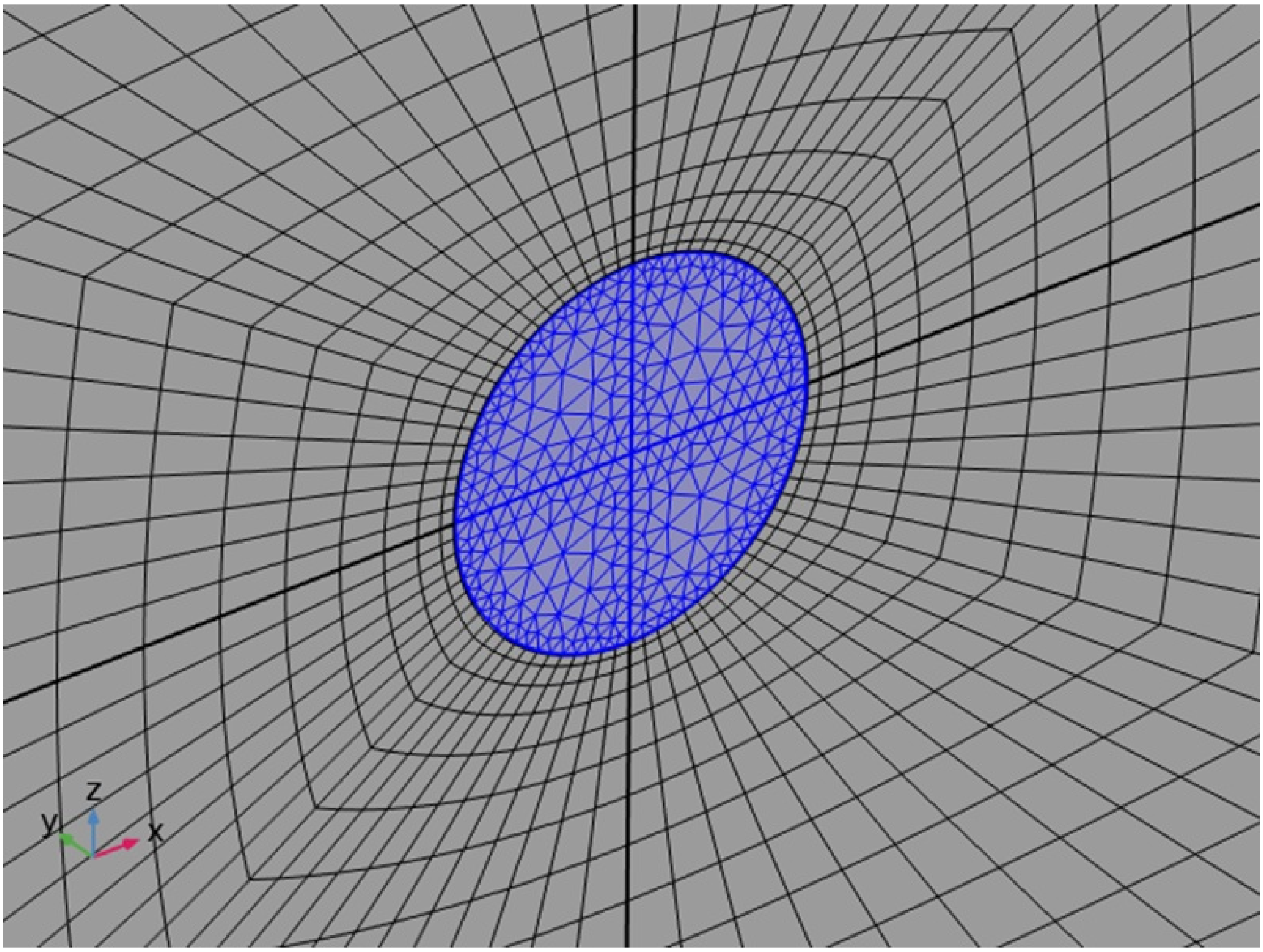

Figure 3 : Figure 3: Coupled interface showing fracture cavity mapped to equivalent geometry for solid mechanics analysis. Interface conditions enforce mass and energy continuity between fluid and solid domains.