

Thermal-Mechanical Model Coupling in Geologic CO₂ Sequestration Simulation

Abstract – An estimated 85% of the world's energy will be derived from fossil fuels by 2030. Mitigating environmental impacts of fossil-fuel combustion on global warming has become a critical issue. With 70% of electricity generated from fossil fuel combustion, CO₂ sequestration in underground aquifer-caprock systems is one solution that is becoming a promising technology for reducing harmful CO₂ emissions created by coal-fired power stations. However, carbon sequestration by injection of CO₂-rich fluids in geologic media is not without risk, as one of the primary fears is the unintentional triggering of small- to moderate-sized earthquakes that can damage the seal integrity of geologic formations that consist of brittle sandstones, which could potentially leak stored CO₂ into the atmosphere. Furthermore, the transport of toxic heavy metals and organic species into fresh water systems can occur through new fractures in caprock formed during CO₂ injection. Stresses resulting from CO₂-rich fluid injection in geologic media may induce rock fracturing. We present a coupled thermal-mechanical model that computes average rock stress, using the Winterfeld-Wu model, as a function of formation temperature, pressure, and hydrologic forces, and is based on the dual porosity model of Aifantis. This average stress model is coupled to a heat-transfer model with a volumetric energy generation source term derived from the revised Helgeson-Kirkham-Flowers (HKF) thermodynamic model for aqueous solute species reactions. The HKF model is based on computing properties of dilute aqueous species by separately considering solvation and nonsolvation contributions. The solvation contribution is based on the Born model for determining the free energy of solvation, where formation water permittivity is calculated using Johnson and Norton regression coefficients. Activity coefficients of electrically charged solutes are approximated using the B-dot model, which is an extended Debye-Hückel model. The HKF derived partial molal heat capacity and enthalpy of charged aqueous species arising from the interaction of CO₂-rich brine with sandstone are used in the source term of a three-dimensional, transient, multiphase heat transfer model. The heat transfer model accounts for the advective and diffusive energy transport of aqueous CO_{2,aq}, gaseous CO_{2,g} and natural gas, pure liquid phases (fresh water, oil), and solid rock phases. Advective transport is modeled using Darcy's law for pressure driven-flow and solved using a finite volume method on a staggered grid. Formation pressure is computed using a poroelastic pore pressure diffusion model and solved using the finite element method. Incremental changes in rock permeability are modeled using an Oda permeability tensor that calculates changes in permeability that result from pressure induced fracturing. The impact of rock fractures on fluid flow in a reservoir are determined by the impact fracturing has on permeability, as fractures increase both the magnitude and anisotropy of permeability because of changes in fracture length and hydraulic aperture, properties used to calculate Oda's permeability tensor. Formation porosity and permeability, as a function of rock stress, is determined using the relations of Gutierrez, Rutqvist, and Ostensen. These distinct models for stress, pressure, and temperature are coupled and used to predict fracture characteristics of a shale-sandstone system that models the Oligocene Frio Formation along the Texas Gulf Coast. Simulation results are compared to bottom-hole pressure data obtained from an observation well 30 meters from an injection well during a sequestration test known as the Frio Pilot Experiment.