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A sequential implicit algorithm of chemo-thermo-poro-mechanics for fractured geothermal reservoirs

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ABSTRACT

We describe the development of a sequential implicit formulation and algorithm for coupling fluid-heat flow, reactive transport, and geomechanics. We consider changes in pore volume from dissolution caused by chemical reactions, in addition to coupled flow and geomechanics. Moreover, we use the constitutive equations for the multiple porosity model for fractured geothermal reservoirs, employing failure-dependent permeability dynamically and updating it every time step. The proposed sequential algorithm is an extension of the fixed-stress split method to chemo-thermo-poro-mechanics, facilitating the use of existing flow-reactive transport and geomechanics simulators.

We first validate a simulator that employs the proposed sequential algorithm, matching the numerical solutions with the analytical solutions such as Terzaghi's and Mandel's problems for poro-mechanics and the reference solutions of chemo-poro-mechanics and chemo-thermo-poro-mechanics in the 1D elastic problems. We also perform convergence test, and the proposed algorithm shows fast convergence, when full iteration is taken, and first order accuracy in time for the staggered approach.

We then investigate two test cases: 2D multiple porosity elastic and 3D single porosity elastoplastic problems, and explore the differences in coupled flow and geomechanics with and without reactive transport. We find that the change in pore-volume induced by mineral dissolution can impact on fluid pressure and failure status, followed by significant changes in permeability and flow variables, showing strong interrelations between flow-reactive transport and geomechanics.

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1. Introduction

Enhanced geothermal reservoirs that exhibit increased permeability resulting from shear stimulation of a fracture volume can provide large heat extraction accompanied by economic flow rates and energy production. Fractures are highly compressible compared with intact rock, so they may affect overall geomechanical responses significantly, even though they occupy a smaller bulk volume (Bai, 1999). Permeability can significantly be affected by deformation of fractures through the relationship between the fracture aperture and permeability (Snow, 1965; Rutqvist and Stephansson, 2003). Furthermore, chemical or thermal nonequilibrium between injection fluid and the reservoir host rock can result in dissolution and precipitation, changing the porosity (Xu et al., 2011). Such changes in pore volume can change fluid pressure, and hence effective stress and strain. Permeability changes through mineral-water reactions and geomechanics affect solute transport which can lead to strong thermal, hydrological, mechanical, and chemical coupling. These physical processes occur simultaneously, but they have different time scales. The geomechanical problem is written as the elliptic partial differential equation (PDE) for modeling quasi-static mechanics, showing the instantaneous mechanical responses (Coussy, 1995; Lewis and Schrefler, 1998), while pressure and saturation equations of the multiphase flow problems are expressed as the parabolic and hyperbolic PDEs, which model time-dependant physical behavior (Aziz and Settari, 1979; Pruess et al., 1999). Reaction between fluid and the porous media can be modeled based on either a rate-independent equation from local equilibrium assumption or a rate-dependent form of kinetic reaction (Moridis et al., 2008; Xu et al., 2008). The different time scales and strong couplings in those physics result in high numeral stiffness and strong nonlinearity, when we solve the coupled mathematical equations numerically, thus robust and rigorous numerical modeling is necessary for accuracy.

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The geothermal reservoirs are naturally or artificially fractured for economic feasibility, consisting of the fracture(s) and rock matrix. The multiple continuum approach is a widely used approach that can represent the fracture-rock matrix systems consisting of a highly permeable fracture continuum transporting fluid over the domain, while the matrix stores fluid and conveys it to the highly permeable fracture continuum (Barenblatt et al., 1960; Berryman, 2002; Sonnenthal et al., 2005; Taron et al., 2009). In geothermal reservoirs, we may introduce more than two continua (e.g., representing fracture and several rock matrix continua) for more accurate modeling of heat flow. Recently, Kim et al. (2012) proposed formulation and sequential numerical algorithms for coupled fluid-heat flow and geomechanics within such a multiple continuum approach. We have implemented these functionalities within ROCMECH, an in-house geomechanics simulator, which is coupled to TOUGH family codes, flow simulators.

The study presented in this paper is based on the latter study, employing nonlinear dynamic strain and failure-dependent permeability in order to capture complex interactions between flow and geomechanics. In this study, we consider changes in pore volume, induced by chemical reaction, when solving for fluid and heat flow. When combining the two simulators, we solve fluid and heat flow, geomechanics, and reactive transport problems sequentially, adopting implicit solution schemes for the subproblems (i.e., sequential implicit method). Specifically, when solving flow and geomechanics, we employ the fixed-stress sequential method, which solves flow first, fixing the total stress field locally, and solves geomechanics at the next step from the calculated flow solutions. The fixed-stress method can provide numerical unconditional stability and high accuracy, comparable to the fully implicit method, regardless of the coupling strength in pore volume between flow and geomechanics (Kim et al., 2011b, 2013, 2012). Taron et al. (2009) employed the undrained sequential method, which solves geomechanics first, fixing fluid mass locally, and then solves flow at the next step. The undrained sequential method can also provide numerical stability in solving flow and geomechanics (Armero, 1999), but causes inaccuracy or non-convergence for the high coupling strength in the case of highly deformable porous media (e.g., fracture) and incompressible fluid (e.g. liquid water) (Kim et al., 2011a). The fixed-stress method can easily be implemented by using the porosity function and its correction (Settari and Mourits, 1998; Kim et al., 2012). In this study, we incorporate the porosity change from chemical reaction into the sequentially coupled simulator, TOUGHREACT+ROCMECH (shortly, T+M). In T+M, flow-geomechanics properties and variables (e.g., porosity, permeability, fluid-phase pressure and saturation, displacement, effective stress, failure status) are updated dynamically along with the transient coupled simulation. We perform several verification test cases for T+M (e.g., the Terzaghi and Mandel problems, 1D elastic chemo-poro-mechanics and chemo-thermo-poro-mechanics problems), as well as their convergence analysis. Then, we investigate 2D and 3D geothermal problems, using coupled thermo-poro-mechanics simulations with and without reactive transport, and analyze differences between them.

2. Mathematical description

We briefly describe the governing equations of geomechanics, fluid and heat flow with reactive solute transport. Next, we introduce constitutive equations for the multiple porosity model and the changes in pore volume from geomechanics and chemical reactions.

2.1. Governing equations

The governing equation for geomechanics is based on the quasi-static assumption, written as (Coussy, 1995)

$$\mathrm{Div}\,\boldsymbol{\sigma} + \rho_b \boldsymbol{g} = \boldsymbol{0}, \tag{1}$$

where Div is the divergence operator, $\boldsymbol{\sigma}$ is the total stress tensor, ρ_b is the bulk density, and $\boldsymbol{g}$ is the gravity vector. The infinitesimal transformation is used to allow the strain tensor, $\boldsymbol{\varepsilon}$, to be the symmetric gradient of the displacement vector, $\boldsymbol{u}$,

$$\boldsymbol{\varepsilon} = \frac{1}{2}(\mathbf{Grad}\,\boldsymbol{u} + \mathbf{Grad}^t\,\boldsymbol{u}), \tag{2}$$

where **Grad** is the gradient operator, and $\mathbf{Grad}^t\,\boldsymbol{u}$ is the transpose of $\mathbf{Grad}\,\boldsymbol{u}$. From here on, tensile stress and strain are positive.

The governing equations for multiphase-multicomponent fluid and heat flow are derived from the conservation law (Pruess et al., 1999), as follows:

$$\frac{d}{dt}\int_\Omega m^k d\Omega + \int_\Gamma \mathbf{f}^k \cdot \mathbf{n}\, d\Gamma = \int_\Omega q^k d\Omega, \tag{3}$$

where the superscript k indicates the fluid component or heat. $d(\cdot)/dt$ means the time derivative of a physical quantity $(\cdot)$ relative to the motion of the solid skeleton. m^k is mass of component k or heat, where the superscript $(\cdot)^\theta$ indicates heat. $\mathbf{f}^k$ and q^k are its flux and source terms on the domain Ω with a boundary surface Γ, respectively, where $\mathbf{n}$ is the normal vector to the boundary.

The mass flow term $\mathbf{f}^k$ in Eq. (3) is given by

$$\mathbf{f}^k = \sum_J (\mathbf{w}_J^k + \mathbf{J}_J^k), \tag{4}$$

where $\mathbf{w}_J^k$ and $\mathbf{J}_J^k$ are the convective and diffusive mass flows of component k in the phase J. When the fluid phase is liquid, $\mathbf{w}_J^k$ is described by Darcy's law as

$$\mathbf{w}_J^k = \psi_J^k\, \mathbf{w}_J$$
$$\mathbf{w}_J = -\frac{\rho_J\, k_{rJ}}{\mu_J}\, \mathbf{k}_p\, (\mathbf{Grad}\, P_J - \rho_J\, \boldsymbol{g}), \tag{5}$$

where $\mathbf{k}_p$ is the second order absolute permeability tensor; ρ_J, μ_J, k_{rJ}, and P_J are the density, viscosity, relative permeability, and pressure of the fluid phase J, respectively. ψ_J^k is the mass fraction of component k in the phase J. In the case that the fluid is gaseous, $\mathbf{w}_J^k$ can be written as

$$\mathbf{w}_J = -\left(1 + \frac{k_K}{P_J}\right) \mathbf{k}_p \frac{\rho_J\, k_{rJ}}{\mu_J}\, (\mathbf{Grad}\, P_J - \rho_J\, \boldsymbol{g}), \tag{6}$$

where k_K is the Klinkenberg factor (Klinkenberg, 1941). The diffusive flow $\mathbf{J}_J^k$ is described as

$$\mathbf{J}_k^J = -\,\Phi\, S_J\, \tau_G\, \mathbf{D}_J^k\, \rho_J\, \mathbf{Grad}\, \psi_J^k, \tag{7}$$

where $\mathbf{D}_J^k$ is the second order hydrodynamic dispersion tensor of component k in the phase J, and τ_G is the gas tortuosity. Φ (Lagrange's porosity, also called reservoir porosity) is defined as the ratio of the pore volume in the deformed configuration to the bulk volume in the reference (typically initial) configuration. S_J is the saturation of the fluid phase J.

The heat flux, $\boldsymbol{f}^\theta$, is obtained by heat conduction and convection laws, written as

$$\boldsymbol{f}^\theta = -\left((1-\Phi)\mathbf{K}_R + \Phi S_J \mathbf{K}_J\right)\mathbf{Grad}\, T + h_J \boldsymbol{w}_J, \tag{8}$$