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A reactive thermo-poroelastic analysis of water injection into an enhanced geothermal reservoir

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ABSTRACT

Coupled thermo-poro-chemo-mechanical processes in geothermal systems impact the reservoir response during injection and production procedures by affecting fracture permeability. A three-dimensional numerical model is presented to analyze these processes during fluid injection into geothermal reservoirs. The solid mechanics aspect of the problem is computed using the displacement discontinuity boundary element method (BEM) while transport processes within the facture are modeled using the finite element method (FEM). The FEM and BEM formulations are integrated to set up a system of equations for unknown temperature, pressure, concentration, and fracture aperture. The fluid diffusion, heat conduction and solute diffusion in the reservoir are treated using BEM so that the need of infinite reservoir domain discretization is eliminated. The numerical model is used to analyze the fracture response to non-isothermal reactive flow in EGS. Numerical examples of SiO_2 undersaturated-cold water injection into the geothermal reservoir show that silica dissolves from the rock matrix, increasing the fracture aperture. The zone of silica dissolution spreads into the fracture with continuous fluid injection. At large injection times, thermoelastic stress has a greater impact on fracture aperture compared to poroelastic stress. Simulations that consider natural fracture stiffness heterogeneity show the development of a non-uniform flow path within the crack, with lower rock matrix cooling and thus enhanced silica reactivity in the high stiffness regions. As a result, areas of higher joint normal stiffness show lower aperture increases in response to the thermo-poroelastic processes, but a higher aperture expansion due to silica dissolution. Depending on the injectate saturation state with respect to quartz, silica is added or removed from the rock matrix. This process is likely to impact the rock matrix properties and its mechanical response to stress perturbations associated with fluid circulation.

1. Introduction

Geothermal energy is extracted by water circulation in natural and/or hydraulically created fractures in hot reservoirs. The circulating fluid that flows through the fracture network interacts with the adjacent rock matrix. The interaction leads to variation in fracture geometry and permeability in response to mechanical, thermal and chemical processes. Different aspects of coupling chemical process with the thermal and mechanical response of the geothermal reservoirs have been studied using numerical formulations (Martin and Lowell, 1997; Wangen and Munz, 2004a,b; Rutqvist et al., 2006; Ghassemi and Kumar, 2005, 2007). It has been observed that the thermoelastic effects dominate near the injection region when compared to those of poroelasticity, and under some conditions, silica reactivity may govern permeability. Kohl et al. (1995) and Ghassemi and Zhou (2011) have studied hydraulic, thermal and elastic perturbations arising from poroelastic and thermoelastic effects in hydraulic fractures and joints. However, chemical reactivity was not treated. Numerical, as well as experimental examinations, have shown the importance of mineral dissolution, precipitation and pressure solution within fractures during fluid injection in geothermal reservoirs (Yasuhara et al., 2003; Yasuhara and Elsworth, 2006; Liu et al., 2006; Elsworth and Yasuhara, 2010). Furthermore, experimental studies (Carroll et al., 1998; Johnson et al., 1998; Dobson et al., 2003) show that chemical precipitation and dissolution of minerals can significantly affect fracture aperture.

Simulating chemical and thermo-poromechanical processes in the fracture-matrix system of a geothermal reservoir involves solving equations that describe fracture and porous medium flow, heat transport, solute transport/reactions and its thermo-poroelastic responses. These equations are obtained by considering constitutive models and transport and balance laws (e.g., fluid

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Nomenclature

A	fracture plane (L^2)
B	Skempton's pore pressure coefficient
c	concentration
c_0	initial concentration
c_i	injecting fluid concentration
c_{eq}	equilibrium concentration
c_j	joint cohesion ($M\,L^{-1}\,T^{-2}$)
c_D	fluid diffusivity coefficient ($L^2\,T^{-1}$)
c_F	specific heat of the fluid ($L^2\,T^{-2}\,K^{-1}$)
c_R	specific heat of the rock matrix ($L^2\,T^{-2}\,K^{-1}$)
D_n	displacement discontinuity (L)
D_F	fluid flux discontinuity ($L\,T^{-1}$)
D_H	heat flux discontinuity ($M\,T^{-3}$)
D_S	solute flux discontinuity ($L\,T^{-1}$)
f_Q	mineral fraction in the reservoir
G	shear modulus ($M\,L^{-1}\,T^{-2}$)
k	rock matrix permeability (L^2)
K	reaction rate constant ($L\,T^{-1}$)
K_R	thermal conductivity of reservoir matrix ($M\,L\,T^{-3}\,K^{-1}$)
K_n	joint normal stiffness ($M\,L^{-2}\,T^{-2}$)
l	total number of element nodes
M	total number of elements
$\mathbf{N}$	element shape function
n	outward normal to fracture
p	excess pore pressure ($M\,L^{-1}\,T^{-2}$)
p_o	ambient reservoir pore pressure ($M\,L^{-1}\,T^{-2}$)
p_n^{iD}	pore pressure caused by an instantaneous D_n ($M\,L^{-1}\,T^{-2}$)
p^{iF}	pore pressure caused by an instantaneous fluid source ($M\,L^{-1}\,T^{-2}$)
p^{iH}	pore pressure caused by an instantaneous heat source ($M\,L^{-1}\,T^{-2}$)
p_i	pressure at injection well ($M\,L^{-1}\,T^{-2}$)
p_e	pressure at production well ($M\,L^{-1}\,T^{-2}$)
q	fluid discharge in the fracture ($L^2\,T^{-1}$)
q_H	heat source intensity ($M\,T^{-3}$)
q_S	solute source intensity($L\,T^{-1}$)
Q_i	fluid injection rate ($L^3\,T^{-1}$)
Q_e	fluid production rate ($L^3\,T^{-1}$)
v_L	fluid leak-off velocity($L\,T^{-1}$)
T	temperature (K)
t	time (T)
T_R	rock temperature (K)
T_i	injection fluid temperature (K)
T_o	ambient rock temperature (K)
u_i	solid displacement components (L)
w	fracture aperture (L)
w_o	initial fracture aperture (L)
x	space coordinate along the flow direction in the fracture (L)
y	space coordinate in the direction normal to the fracture (L)
z	space coordinate in the direction normal to the fracture (L)
$\mathbf{x}$	vector of influence point coordinates (L)
$\mathbf{x}'$	vector of influencing point coordinates (L)

Greek symbols

α	Biot's effective stress coefficient
α_T	linear thermal expansion coefficient (K^{-1})
β_s	volumetric thermal expansion coefficient (K^{-1})
δ	Dirac delta function
ε_{ij}	strain components
ε	volumetric strain
μ	viscosity of the fluid ($M\,L^{-1}\,T^{-1}$)
ν	drained Poisson's ratio
ν_u	undrained Poisson's ratio
ϕ	joint friction angle
ρ_F	density of the fluid ($M\,L^{-3}$)
ρ_R	bulk density of the reservoir matrix ($M\,L^{-3}$)
ρ_Q	density of the mineral ($M\,L^{-3}$)
σ_{nn}^{iD}	stress components caused by an instantaneous D_n ($M\,L^{-1}\,T^{-2}$)
σ_n^{iF}	stress components caused by an instantaneous fluid source ($M\,L^{-1}\,T^{-2}$)
σ_n^{iH}	stress components caused by an instantaneous heat source ($M\,L^{-1}\,T^{-2}$)
σ_{n0}	initial stress components ($M\,L^{-1}\,T^{-2}$)
σ_n	normal stress component to fracture ($M\,L^{-1}\,T^{-2}$)
σ_v	vertical in situ stress ($M\,L^{-1}\,T^{-2}$)
σ_h	minimum horizontal in situ stress ($M\,L^{-1}\,T^{-2}$)
σ_H	maximum horizontal in situ stress ($M\,L^{-1}\,T^{-2}$)
Ω	volume of the domain of interest (L^3)
Δt	time increment (T)
∇^2	Laplacian operator in three dimensions

momentum, fluid continuity) are generally coupled and require complex, numerical solutions. Simple analytical solutions for silica dissolution and precipitation processes due to thermo-poroelastic fracture deformation during injection/production procedure have been formulated by assuming uniform fluid velocity in the line fractures and one-dimensional fluid leakoff (Rawal and Ghassemi, 2008). In this paper, we present a 3D numerical model to investigate silica dissolution/precipitation and fracture aperture variation in response to poro- and thermo-mechanical processes during fluid injection/production in enhanced geothermal systems (EGS). We use a partially coupled 3D thermo-poroelastic approach with the displacement discontinuity method (Ghassemi and Zhou, 2011) to compute the mechanical response of the fracture/matrix system. Reactive solute transport in the fracture is modeled using the finite element method, while 3D heat/fluid/solute diffusion in the rock matrix is modeled using the boundary integral equation method, eliminating the need for infinite reservoir domain discretization. Numerical examples are presented to investigate the effects of silica dissolution/precipitation and thermo-poroelasticity associated with cold water injection for heat extraction in EGS.

2. Modeling approach and governing equations

The problem has four components: fluid flow, heat transfer, solute transport and fracture aperture change. These are briefly described in the following sections. The fracture is considered to be of finite size, contained in a matrix of infinite extent and has a small aperture varying smoothly such that the incompressible fluid flow in the fracture is laminar and two-dimensional. Poroelastic and thermoelastic properties of the reservoir rock and fluid are considered constant.

2.1. Fluid flow in the fractures and reservoir matrix

Assuming the fluid flow to be laminar and the lubrication theory applies so that the momentum balance for the fluid can be written