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Coupled Thermo-Hydro-Mechanical (THM) model for Geothermal Energy Extraction from Fractured Rock Masses

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Summary

Switching from traditional and fossil fuels to renewable and low carbon energy resources is urgently needed to address climate change concerns; various integrated solutions to tackle the environmental challenges will be needed. Among geothermal resource types, as renewable (or at least vast) resources, Hot Dry Rocks (HDRs) with very low permeability and insignificant fluid porosity are common all over the world at various depths. Enhanced Geothermal Systems (EGSs) are the accepted method for extracting heat from HDRs where fractured rock zones are created using hydraulic fracturing techniques. Heat extraction from the fractured rock masses encompasses several coupled processes caused by interaction of the cold water and hot rock. The mutual effects of rock state and properties, fluid properties and rates, and cooling strains can lead to geomechanical consequences such as volume shrinkage, stress changes, , reactivation of preexisting faults or the generation of new fractures, seismic events, fracture aperture alterations, changes in rock mass permeability, etc. Evaluating the mutual impacts of variations in temperature, deformation, and pressure in the reservoir, as a multiphysics problem, requires coupled Thermo-Hydro-Mechanical (THM) analysis. This process is more important for determining the dimensions of the reservoir, injection flow rate, the number of wells, etc., for specific amounts of heat extraction for rock masses with specific geological and geomechanical characteristics.

Introduction

Analytical and semi-analytical studies, besides their deep and comprehensive representation of EGS behavior, have the drawback of many simplifying assumptions due to the highly sophisticated situation in the reservoir, which may be too complex to address in a purely analytical solution with regular geometry (Cheng *et al*. 2001, Ghassemi *et al*. 2008, Wang *et al*. 2016). Numerical coupled THM models are thus necessary for generating more precise and reliable results by considering all reasonably expected assumptions. The coupling of heat transfer, fluid flow, and stress/strain in the fractured rock mass has been an object of research since the early 1980s in rock mechanics and engineering designs (Tsang 1987, 1991). Using THM coupling in geothermal systems was first implemented in the early 1990's. Hicks *et al*. (1996) presented a 2D numerical model of THM in naturally fractured rock and applied it to assessments of HDR. Salimzadeh *et al*. (2018a) presented a 3D coupled THM finite element model for a deformable fractured geothermal reservoir to analyze the fracture aperture changes, which directly influences the fluid velocity, output temperature, and stress field.

Workflow

THM coupling analysis requires integration of the conservation of mass, momentum, and energy and constitutive laws. The governing equations of the coupled THM process for a discrete fracture within a deformable rock matrix are presented as follows (Figure 1) (Ghassemi and Zhou 2011, Salimzadeh *et al*. 2018b).

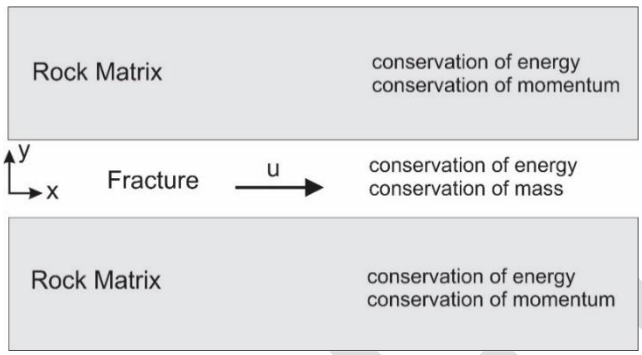

Figure 1: A schematic view of a discrete fracture within a deformable rock matrix.

Conservation of momentum (stress equilibrium): Under quasi-static assumptions and non-isothermal conditions for the rock matrix, the linear momentum balance equation is

$$\boldsymbol{\nabla} \cdot \boldsymbol{\sigma} + \boldsymbol{b} = \boldsymbol{0} \tag{1}$$

in which $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\boldsymbol{b} = \rho \boldsymbol{g}$ is the body force per unit volume, ρ is the bulk density, and $\boldsymbol{g}$ is the gravity vector.

Constitutive law: Assuming small deformations and linear elasticity, the constitutive law for the stress-strain relationship in the rock matrix is described as

$$\boldsymbol{\sigma} = \mathbb{C} : \boldsymbol{\varepsilon} \tag{2}$$

in which $\mathbb{C}$ is the fourth-order elasticity tensor expressing material behavior, and $\boldsymbol{\varepsilon}$ is the linear strain tensor.

Conservation of energy: Assuming a homogeneous static medium, the energy balance equation for heat transfer, is given as

$$-\boldsymbol{\nabla} \cdot \boldsymbol{q}_r^T + S_r = \rho_r c_r \frac{\partial T_r}{\partial t} \tag{3}$$

where $\rho_r c_r$ is the heat storage capacity of the rock, S_r is the sink/source term, and T_r is the temperature of rock. Assuming a non-porous rock matrix, the heat flux ($\boldsymbol{q}_r^T$) can be expressed by Fourier's law:

$$\boldsymbol{q}_r^T = -\boldsymbol{K}_r \boldsymbol{\nabla} \mathrm{T}_r \tag{4}$$

in which $\boldsymbol{K}_r$ is thermal conductivity of the rock matrix.

Conservation of mass: The governing equation for fluid flow through a discrete fracture with no infill materials can be described as

$$\frac{\partial a_f}{\partial t} = \boldsymbol{\nabla} \cdot \boldsymbol{q}_l^c + S_f \qquad (5)$$

where a_f is the equivalent fracture aperture for flow , $\boldsymbol{q}_l^c$ is fluid flux, and S_f is a sink/source term.

Assuming an incompressible fluid with laminar flow within the fracture idealized as two parallel plates, fluid flux is given by the cubic law as (Witherspoon *et al*. 1980).

$$\boldsymbol{q}_l^c = -\frac{{a_f}^3}{12\mu}\boldsymbol{\nabla} p \qquad (6)$$

in which p is the fluid pressure, and μ is the fluid dynamic viscosity.

Conservation of energy: The advection-diffusion term in the fluid is governed by conservation of energy as

$$\rho_l c_l \boldsymbol{V}.\boldsymbol{\nabla} T_l + \boldsymbol{\nabla} \cdot \boldsymbol{q}_l^T - S_l = \rho_l c_l \frac{\partial T_l}{\partial t} \qquad (7)$$

in which $\boldsymbol{q}_l^T = -\boldsymbol{K}_l \boldsymbol{\nabla} \mathrm{T}$ is Fourier's law for fluid, $\boldsymbol{K}_l$ is the thermal conductivity of the fluid, $\boldsymbol{V}$ is the fluid velocity through the fracture, S_l is the sink/source term, and T_l is fluid temperature.

The following assumptions are considered in the current study:

- EGS reservoirs are in Hot Dry Rocks (HDRs) with very low permeability, such as granite. Matrix permeability is ignored; all fluid is assumed to flow through the fracture network.
- The simulation is performed in two dimensions (2D) and under plane-strain conditions.
- Conduction and convection (advection-diffusion) heat transfer mechanisms are considered in the rock matrix and for fluid flow, respectively.
- A transient heat transfer mechanism for the rock matrix and a steady-state condition in the energy balance equation for the fluid domain and in the mass balance equation for the fracture are assumed.
- An EGS's lifetime is ≈30-40 years and is defined mainly on the rock mass temperature decreasing slowly via conductive heat transfer over time. Fluid temperature and fracture aperture changes within each time step are assumed negligible with respect to the fluid velocity. Thus, rock matrix heat transfer is assumed to be transient, while energy and mass balance equations for the fracture are assumed to be steady state.

Results

Because of the complexity and high computational cost of modeling a real situation in a naturally fractured EGS reservoir, many studies focus on a single fracture model representing the main flow path to represent a simple EGS reservoir as a limiting case.

A two-dimensional (2D) finite element method (FEM) program has been developed under plane-strain conditions for the THM process in the EGS reservoir arising from cold water injection.

The model domain comprises a horizontal fracture embedded within the very low permeability granite rock. The simulation considers a 3000 m long × 1000 m high domain, respectively. The boundaries are far enough away so that boundary effects do not impact the 30-year results. A fracture is considered in the middle of the domain, as a simple representation of an EGS reservoir, and is intersected by the injection and extraction wells (Figure 2).

Water is injected through the fracture at a constant rate of 10 l/s and a constant temperature of 50$°C$. The initial temperature of the rock matrix is assumed to be 200$°C$. The far-field temperature on the boundaries is considered constant. Fluid flow is exclusively through the fractures, since the rock matrix has extremely low permeability. For heat transfer, the effects of the very low permeability rock matrix and leak-off are negligible to the overall heat transfer over the EGS project time scale (over years). Therefore, leak-off from the fracture into the rock matrix is negligible and ignored in the model. Table 1 illustrates the parameters used in this model.

Table 1: Fluid, rock, and fracture properties used in the THM coupled modeling.

Property name	**Value**
Initial fracture aperture	0.1 (mm)
Reservoir pore pressure	35 (MPa)
Reservoir temperature	200 (^oC)
Rock density	2650 (kg/m^3)
Rock Poisson's ratio	0.25
Rock Young's modulus	70 (GPa)
Rock bulk modulus	35 (GPa)
Specific heat capacity of rock	900 (J/kg/K)
Rock thermal conductivity	2.690 (W/m/K)
Linear thermal expansion of rock	8×10^{-6} (1/K)
Fluid density	1000 (kg/m^3)
Specific heat capacity of fluid	4200 (J/kg/K)
Fluid thermal conductivity	0.6 (W/m/K)
Fluid dynamic viscosity	0.001 (Pa·s)
Injection temperature of fluid	50 (^oC)
Injection rate of fluid	10 (l/s)
Extraction pressure	30 (MPa)

The production well output temperature is the most important parameters for assessing economic viability of an EGS project as it is used to sustain the Rankine power cycle and is an input parameter for the evaporator during exergy evaluation. Therefore, knowing the geoparameters that impact the output fluid temperature is of the utmost importance for reservoir management (i.e., deciding on the number of wells, reservoir dimension, rate of injection, etc.). Various injection flow rates and fracture lengths affect the output fluid temperature.

As the rock matrix temperature declines, the output fluid temperature starts decreasing after some injection. Figure 3 illustrates the output fluid temperature at the production well over 30 years.

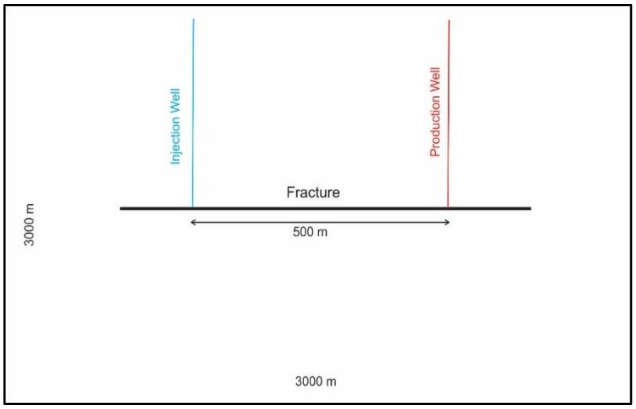

Figure 2: Schematic view of the model geometry for a single fracture in 2D.

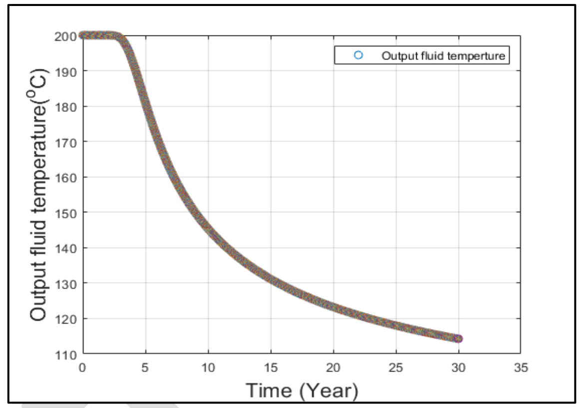

Figure 3: The output fluid temperature at the production well over 30 years.

Conclusions

THM modeling demonstrated that the fracture aperture, and consequently the fracture flow capacity, increased over the long-term heat production from the EGS reservoir. The output fluid temperature is constant and equal to the reservoir's temperature during the first months, depending on the fracture length and injection flow rate; thereafter it decreases. Different rock masses with specific geological and geomechanical characteristics can be evaluated using the model to check whether or not it can generate required heat and be commercially successful.

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