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Production optimization in fractured geothermal reservoirs by coupled discrete fracture network modeling

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ABSTRACT

In this work, a stimulation then heat production optimization strategy is presented for prototypical EGS geothermal reservoirs by comparing conventional stimulation-then-production scenarios against revised stimulation schedules. A generic reservoir is selected with an initial permeability in the range of 10^{-17}–10^{-16} m^2, fracture density of ~0.09 m^{-1} and fractures oriented such that either none, one, or both sets of fractures are critically stressed. For a given reservoir with a pre-existing fracture network, two parallel manifolds are stimulated that are analogous to horizontal wells that allow a uniform sweep of fluids between the zones. The enhanced connectivity that develops between the injection zone and the production zone significantly enhances the heat sweep efficiency, while simultaneously increasing the fluid flux rate at the production well. For a 10 m deep section of reservoir the resulting electric power production reaches a maximum of 14.5 MWe and is maintained over 10 years yielding cumulative energy recoveries that are a factor of 1.9 higher than for standard stimulation. Sensitivity analyses for varied fracture orientations and stimulation directions reveal that the direction of such manifolds used in the stimulation should be aligned closely with the orientation of the major principal stress, in order to create the maximum connectivity. When the fractures are less prone to fail, the output electric power is reduced by a decrease in the fluid flux rate to the production well.

1. Introduction

Enhanced geothermal reservoirs (EGS) have been shown to be a viable resource for the recovery of thermal energy. However, due to their intrinsic characteristics of low permeability and porosity they have been proved intractable in developing sufficient fluid throughput by stimulation. The principal challenge has been in developing adequate permeability in the reservoir that also retains sufficient heat transfer area (Tester et al., 2006).

Numerical simulation is an essential approach to investigate coupled multi-physics processes (Thermal-Hydraulic-Mechanical) and to better understand the fundamental mechanisms and feedbacks that occur in geothermal reservoirs. This is particularly important due to the intense pressure-sensitivity of fractures in the coupling of permeability and heat transfer area (Taron and Elsworth, 2009). From previous studies, thermal quenching and resulting contractile strains may substantially unload the reservoir and increase both fracture aperture and permeability via creep or by induced seismicity and fault reactivation (Gan and Elsworth, 2014a,b; Segall and Fitzgerald, 1998). This may occur close-in to the wellbore at early times and at later times in the far-field when larger features and faults may be affected (Elsworth et al., 2010; Taron and Elsworth, 2010a). For discretely fractured rock masses, there are two major approaches to simulate the influence of randomly distributed fractures. One approach is to represent the fractured mass as a continuum where the aggregate response is represented (Taron and Elsworth, 2010b) and an alternative is a discontinuum approach (Ghassemi and Zhang, 2006; McClure and Horne, 2013; Min and Jing, 2003; Pine and Cundall, 1985) where individual fractures are discretized and their individual response followed. Continuum methods have the advantage of effectively simulating behavior at large (field) scale and for the long-term due to the lower computational requirements. The behavior of fractures is implicitly included in the equivalent constitutive models for both deformation and transport. The central effort in developing the equivalent continuum approach is the incorporation of crack tensor theory (Oda, 1986). This is different in behavior from the application of discrete fracture network models (DFNs) where the behavior of individual fractures is explicitly

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represented in the macroscopic response. In previous work (Gan and Elsworth, 2016), an equivalent continuum T-H-M coupled simulator TF_FLAC^{3D} has been developed to investigate the evolution of stress-dependent fracture permeability in equivalent DFNs. The benefits of this continuum simulator are in mechanically representing the fractured mass by adopting a crack tensor, but also in simulating the heat and mass transport by advection and in the long term, albeit for continuum problems.

Strategies for optimizing production (high flowrate, high temperature and long duration) in geothermal reservoirs have been explored (Marcou, 1985; Akın et al., 2010; Pham et al., 2010) by identifying the impact of various parameters on thermal extraction, and in proposing strategies to enhance thermal power generation. The rate of heat energy production is defined by the effluent water temperature and flow rate from the production well. The ideal condition is to maintain both a high flux rate and high temperature for as long as possible, while simultaneously delaying thermal breakthrough to the production well. The reservoir volume (and temperature) is the key parameter that determines the cumulative magnitude of energy production over the entire reservoir life (Sanyal et al., 2005). This reservoir volume is in turn influenced by the well separation distance as the reservoir volume scales with the "square" of this separation for a typical doublet injection-recovery system (Vörös et al., 2007). In addition to reservoir volume and geometry, the characteristics of the injected fluid also exert some influence. Water density changes little in non-boiling systems but water viscosity may change by a factor of two or three with a change in temperature of 100–200 °C and may therefore exert a direct impact on thermal production (Watanabe et al., 2000). In addition to the ultimate recovery of thermal energy from the system, the rate of recovery is also important.

Dimensionless solutions are useful in defining the rate limiting processes and dependent properties for energy recovery. These simplified models capture the essence of the conductive heat supply to the convecting heat transfer fluid and define this process as the rate limiting step (Elsworth, 1989, 1990; Gringarten and Witherspoon, 1973; Gringarten et al., 1975; Pruess and Wu, 1993; Shaik et al., 2011). The dimensionless parameter controlling the effectiveness of thermal recovery scales with the product of mass flow rate and fracture spacing to the second power (Gan and Elsworth, 2014b) thus defining the principal desire for small spacing between fractures in draining the heat from the fracture-bounded matrix blocks.

Circulating fluids at low rate per unit volume of the reservoir but to access small spacing between fractures is the principal requirement of a successful EGS system. The optimal scenario in production is to establish a uniform fluid-, and thereby thermal-sweep, of the reservoir. The divergent flow field close to the point-source injectors in doublet systems is not effective in providing a uniform sweep, but flow from parallel wells or from stimulated parallel wells offers a better prospect of establishing a uniform flow field. In the oil and gas industry, the drilling and stimulation of parallel, and typically horizontal, wells has been developed to considerable success for unconventional reservoirs, over the past decade. In this work, a new stimulation strategy is explored that comprises the development of two parallel and high permeability manifolds each as a separate injection zone and production zone. It is anticipated that this stimulation schedule will generate analogous results to the drilling of two horizontal wells and therefore in increasing the flow sweep efficiency from the injection zone towards the production zone. The influence of different stimulation strategy and slip potential in the heat transportation and followed heat generation are evaluated in this work.

2. Model

To implement an equivalent continuum model accommodating the fractured mass, the key constitutive relations require to be incorporated. These are the formulations for a crack tensor, a permeability tensor, and a model for stress-dependent fracture aperture.

2.1. Crack tensor

To represent the heterogeneous distribution of components of fractured rock in the simulation, the mechanical properties of fractures are characterized in tensor form based on the crack tensor theory proposed by Oda (1986). The theory is based on two basic assumptions: (1) individual cracks are characterized as tiny flaws in an elastic continuum; and (2) the cracks are represented as twin parallel fracture walls, connected by springs in both shear and normal deformation. By predefining the fracture properties, such as position, length, orientation, aperture, and stiffness, we implement crack tensor theory as a collection of disc-shaped fractures in a 3D system, and modify the distribution of modulus corresponding to the fractured rock and intact rock in each intersected element. Here the intact rock is assumed to be isotropic, the conventional elastic compliance tensor M_{ijkl} for intact rock is formulated as a function of Poisson ratio, ν, and the Young's modulus of the intact rock, E, as

$$M_{ijkl} = \frac{(1+\nu)\delta_{ik}\delta_{jl} - \nu\delta_{ij}\delta_{kl}}{E} \tag{1}$$

The compliance tensor C_{ijkl} for the fractures are defined as a function of fracture normal stiffness K_{nf}, fracture shear stiffness K_{sf}, fracture diameter D, and components of crack tensors F_{ij},F_{ijkl} respectively.

$$C_{ijkl} = \sum^{\text{fracnum}} \left[\left(\frac{1}{K_{nf}D} - \frac{1}{K_{sf}D} \right) F_{ijkl} + \frac{1}{4K_{sf}D} \left(\delta_{ik}F_{jl} + \delta_{jk}F_{il} + \delta_{il}F_{jk} + \delta_{jl}F_{ik} \right) \right] \tag{2}$$

where *fracnum* is the number of fractures truncated in an element block, δ_{ik} is the Kronecker's delta. The related basic components of crack tensor for each crack intersecting an element are defined F_{ij} as below (Rutqvist et al., 2013),

$$F_{ij} = \frac{1}{V_e}\frac{\pi}{4}D^3 n_i n_j \tag{3}$$

$$F_{ijkl} = \frac{1}{V_e}\frac{\pi}{4}D^3 n_i n_j n_k n_l \tag{4}$$

$$P_{ij} = \frac{1}{V_e}\frac{\pi}{4}D^2 b^3 n_i n_j \tag{5}$$

where F_{ij}, F_{ijkl}, P_{ij} are the basic crack tensors, b is the aperture of the crack, V_e is the element volume, and n is the unit normal to each fracture. Therefore the formula for the total elastic compliance tensor T_{ijkl} of the fractured rock can be expressed as,

$$T_{ijkl} = C_{ijkl} + M_{ijkl} \tag{6}$$

Combining Eqs. (3)–(5) into Eq. (2), the equivalent fracture Young's modulus E^f and Poisson ratio ν^f can be obtained as,

$$E^f = \frac{1}{\frac{1}{E} + (\frac{1}{K_{nf}} - \frac{1}{K_{sf}})\frac{1}{V_e}\frac{\pi}{4}D^2 n_1^4 + \frac{1}{K_{sf}}\frac{1}{V_e}\frac{\pi}{4}D^2 n_1^4} \tag{7}$$

$$\nu^f = \frac{\nu}{E}E^f - (\frac{1}{K_{nf}} - \frac{1}{K_{sf}})\frac{E^f}{V_e}\frac{\pi}{4}D^2 n_1^2 n_2^2 \tag{8}$$

Given the assumption that the properties of modulus are anisotropic, the equivalent bulk modulus K and shear modulus G for the fractured rock mass are formulated as below,

$$K = \frac{1}{\frac{1}{K_{\text{int}\,act}} + \sum^{fracnum} \frac{V_{ratio}}{b} \left[(\frac{1}{K_{nf}} - \frac{1}{K_{sf}}) \left(1 - n_2^4\right) + \frac{1}{K_{sf}} n_1^2 \right]} \tag{9}$$