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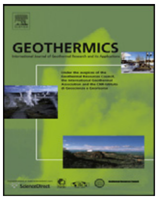

Sustainable heat farming: Modeling extraction and recovery in discretely fractured geothermal reservoirs

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ABSTRACT

Although many natural hydrothermal geothermal systems have been shown to be productive over long periods of time, limited field testing of Enhanced or Engineered Geothermal Systems (EGS) has prevented adequate assessment of their sustainability. To estimate how renewable EGS reservoirs might be, an analytical approach employing Green's function was used to model transient thermal conduction in an idealized reservoir containing a single rectangular fracture to evaluate heat transfer effects during alternating periods of extraction and recovery. During recovery, the temperature along the fracture surface approaches the temperature of the bulk rock with the deviation from the surrounding bulk temperature decaying as $1/\sqrt{t}$ where t is the recovery time. Numerical simulations of a multiple parallel fracture reservoir using the TOUGH2 code agreed with the derived analytical solutions over a range of flow rates and interfracture spacings with only small deviation due to multidimensional effects. Multidimensional effects are more pronounced near the inlet and outlet of the fracture and are reduced at higher flow rates. Thermal interactions between sufficiently spaced fractures are negligible for production periods of 10–30 years, suggesting that the single fracture analytical model can be applied to multifracture reservoirs provided that the mass flow used is on a per fracture basis. Simulation results show that multifracture EGS reservoirs have a greater capacity to sustain high outlet temperatures, suggesting that conductively dominated EGS systems can be regarded as renewable over time scales of societal utilization systems (three to five times the heat extraction time).

1. Introduction

The practical utilization of geothermal energy requires extracting or mining the stored thermal energy contained in the Earth's crust, often several kilometers deep. Today, geothermal energy reservoirs exploit naturally occurring hydrothermal aquifers with high permeability and porosity and sufficient quantities of water or steam. Unfortunately, nature does not always provide these ingredients in locations with large temperature gradients. Engineered or Enhanced Geothermal Systems (EGS) offer technologies that can be implemented in areas with low permeable and/or porous rock formations that do not contain enough water and/or steam or lack sufficient interwell connectivity. In most EGS reservoirs, the rock formations must be stimulated, typically using hydraulic pumping resulting in fracturing or hydroshearing to open pre-exiting sealed fractures. In this manner, the reservoir is engineered, creating open fractures and connectivity where liquid water can then flow under increased pressure through the fracture system to extract heat by contacting regions of hot rock.

One important feature of any operating geothermal reservoir system is its anticipated production sustainability over the long term. In simple terms, the heat mining process removes the stored thermal energy faster than it can be supplied by steady state conduction. Although geothermal reservoirs will be depleted during production, with proper management, hydrothermal reservoirs have been shown to be productive over long periods of time (Axelsson et al., 2005; Bromley et al., 2006). The situation is different for EGS as there is no record of long term field testing and as a result, the renewability of EGS is often questioned. Axelsson et al. (2001) define the renewability of a geothermal resource as the ability to maintain the installed capacity indefinitely. Strictly

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speaking, to maintain capacity indefinitely, the reservoir would have to operate in steady state where the rate of heat extraction from the reservoir is equal to the rate of recharge of thermal energy coming back into the reservoir from the surrounding bulk rock. Unfortunately, due to practical requirements for production, plant needs, and operation costs, the renewable capacity is often too small for commercial development (Sanyal, 2005). Therefore, considerations about the sustainability of geothermal systems must also include the thermal recovery that occurs during a pause in heat extraction. Megel and Rybach (2000) explore the sustainability of a low temperature (62 °C) hydrothermal doublet used for district heating. By allowing for thermal recovery after a period of thermal extraction, they concluded that because the hydrothermal doublet renews itself on a time scale comparable to extraction, it can be operated in a sustainable manner. Sanyal (2005) defines the sustainable capacity of a geothermal reservoir as the capacity that can be economically maintained over the amortized life time of a power plant. In this study, we attempt to quantify the recovery of the reservoir on an absolute basis in terms of its thermal productivity irrespective of any power plant or surface installation life time considerations. Note that unfortunately, recovery is sometimes used as a synonym to thermal extraction (e.g., Elsworth, 1989) in the sense that thermal energy is recovered from the subsurface for use in the surface installation. To avoid confusion, in this study extraction is used to denote the process of removing heat from the subsurface while recovery describes the process of heat from the surrounding hot rock transferring back into the reservoir after extraction has stopped.

Although exploiting an EGS reservoir at an economically useful rate eventually results in significant local cooling of the reservoir, there are valid reasons to consider such geothermal resource operations as sustainable. Complete recovery of the thermal energy is eventually guaranteed following the discontinuation of all production as heat is conducted and convected to the surrounding hot rock that contains the active reservoir. Even with recovery times of hundreds of years, the resource base is large enough to allow for long term sustainable energy production on a national or global scale (Tester et al., 2006). Additionally, geothermal resources can be considered renewable on time scales of technological/societal systems, 10–100 years, whereas fossil fuel reserves “renew” on geologic time scales of order hundreds of million years (Rybach et al., 2000). Furthermore, displacement of fossil fuel consumption with geothermal or other renewables would reduce environmental pollution and help to preserve hydrocarbons for future generations as raw materials and chemical feedstocks as well as for cleaner and more efficient power applications (Sanyal, 2005).

To guarantee the long term sustainability and renewability of a specific EGS reservoir or field development would require implementing a heat farming strategy. Under this approach, several EGS reservoirs would be used in a rotating manner. When the first reservoir is “depleted” to a point where it is no longer able to satisfy the thermal needs of the surface installation, production would be shifted to a new reservoir. The process would continue until the first reservoir has recovered sufficiently to be restarted or restimulated.

The main objective of this work is to evaluate how effectively model geothermal reservoirs recover following extraction. An analytical and numerical model were used to characterize the transient thermal hydraulic behavior of a fractured EGS reservoir. The analytical model considers an idealized system with single and multiple parallel isolated fractures embedded in a large body of impermeable rock with uniform properties. In this situation, heat transfer is dominated by transient conduction perpendicular to the fracture surface coupled to convection of heat by the fluid flowing along the fracture. The TOUGH2 numerical code developed at the Lawrence Berkeley National Laboratory (Pruess et al., 1999) was used for modeling multiple parallel fractures with two-dimensional transient heat conduction within the rock to test the assumptions of the analytical model.

Although the parallel multi-fracture system is highly idealized and is impossible to replicate in practice, such a simple model was chosen to capture the basic behavior of a conduction dominated EGS reservoir undergoing alternating phases of extraction and recovery. This behavior is relevant to evaluating the sustainability of EGS and has been virtually ignored by other researchers. Although our model only represents thermal modeling of a very idealized, conduction dominated EGS reservoir, we feel it illustrates the limiting behavior one might expect in practice – therefore providing a conservative evaluation of sustainability. Real EGS reservoirs will, of course, contain nonlinear coupled thermal, hydraulic, mechanical, and chemical (THMC) processes. However, introducing these features into the analytical model would not result in tractable solutions relevant to the main objective of the paper.

Much research has been done in addressing nonlinear and coupled phenomena in EGS reservoirs. Kohl et al. (1995) modeled coupled THM processes in a single fracture using linear thermo-poroelastic effects and a logarithmic closer law and learned that these effects lead to significant long term reduction in impedance of flow. Willis-Richards and Wallroth (1995) summarized the current EGS modeling at the time and emphasized the importance of accurately capturing the evolution of aperture near the injection and production well, large scale permeability enhancement through means of fracture extension, and heat conduction in the reservoir. Taron and Elsworth (2009) studied THMC coupling effects in a dual porosity media where porosity and permeability change as a result of change of stress and chemical precipitation and dissolution. Their numerical simulations indicate that mechanical effects dominate in the short term (days), while thermal effects are important in the intermediate term (months) and chemical effects are only important in the long term (years). Simulations also reveal that coupling of these effects are needed to explain observed phenomena that parallel reactive transport and geomechanic simulations cannot capture. Ghassemi and Zhou (2011) coupled fracture flow and heat transport to thermo-poroelastic deformation in a discretely fractured reservoir and found the resulting temperature, pressure, stress, and aperture at every time step. Their numerical model revealed that poroelastic effects are dominant at early stages while thermoelastic effects take over at later time and coincide with less leakoff to the far field and significant increase in fracture aperture.

2. Analytical model

A representation of a parallel discretely fractured EGS reservoir, adapted from earlier works by Gringarten et al. (1975) and Wunder and Murphy (1978), is pictured in Fig. 1. For a single fracture model, the fracture spacing x_s goes to infinity. Although realistic reservoirs consist of a network of fractures, a single fracture model adequately captures the essential features of thermal extraction through heat conduction from the rock surrounding the fracture. A single rectangular, vertical fracture of constant width $2b$ separates two blocks of homogeneous, isotropic, impermeable rock. The orientation of the fracture does not matter because buoyancy driven flow is not considered; however, hydraulic stimulation of a reservoir will usually yield vertically oriented fractures because fractures propagate in the direction normal to the plane of least principal stress. A Cartesian coordinate system has been placed such that $x, z = 0$ coincides with the inlet.