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Changes in fracture aperture and fluid pressure due to thermal stress and silica dissolution/precipitation induced by heat extraction from subsurface rocks

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Abstract

The numerical model developed by Suresh Kumar and Ghassemi [Suresh Kumar, G., Ghassemi, A., 2005. Numerical modeling of non-isothermal quartz dissolution in a coupled fracture–matrix system. Geothermics 34, 411–439] is used to study fluid pressure and permeability changes in a fracture in a rock mass by taking into account the effects of thermal stresses and silica precipitation/dissolution, which is computed using linear reaction kinetics. Fluid flow in the fracture is calculated based on the cubic law. Solute transport mechanisms by advection and dispersion are included in the model. Mass exchange between the horizontal fracture and the rock matrix is accounted for by assuming diffusion-limited solute transport. Heat transfer between the fracture and the rock matrix is modeled considering only conduction, while heat transport within the fracture includes thermal advection, conduction, and dispersion in the horizontal plane. Pressures of the circulating fluid through the fracture are allowed to vary with time, while the flow rate is assumed to remain constant.

A series of numerical experiments are carried out to simulate a fluid injection/production operation. The temporal variation of fracture aperture in response to the individual and combined effects of thermal stress and silica dissolution/precipitation is examined. The results show that, for lower initial fracture apertures, the significant increase in fracture permeability and the associated pressure drop at the injection point are mostly attributable to thermoelastic effects, while the increase in fracture aperture near the production well is mainly the result of silica dissolution. On the other hand, for larger initial apertures, the effects of silica precipitation/dissolution are minimal and thermoelastic effects are prevalent, as the intensity of coupling between the high-permeability fractures and the low-permeability rock matrix becomes weaker.

Keywords: Enhanced Geothermal System; EGS; Fracture aperture; Fracture permeability; Thermoelasticity; Silica precipitation; Silica dissolution

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1. Introduction

Hot subsurface rocks that can be reached by means of conventional drilling methods are potentially a very large source of renewable energy (e.g. Abé et al., 1999). This heat can be recovered by (1) creating new, or enhancing the natural, fracture permeability of the rocks, (2) injecting water from the surface into these fractures through wells, (3) circulating this water through the newly developed fracture network where it gains heat, (4) carrying this water to the surface via production wells, (5) using the hot water to generate electricity or in direct applications (e.g. heating), and, finally, (6) injecting the heat-depleted fluid back into the subsurface to close the loop. This method to extract and exploit the heat stored in underground rocks has been called Engineered or Enhanced Geothermal Systems (EGS; Sanyal and Buttler, 2004).

It is generally accepted that the geological conditions favorable for the creation of an EGS include pre-existing, critically stressed and optimally oriented fractures that can be made more permeable through various techniques such as hydraulic, thermal, and chemical stimulation (Combs et al., 2004). The ability to understand and predict changes in fluid and heat production that occur as the geothermal fluid circulates between the injection and production wells is complicated by poro-mechanical, thermal, and geochemical processes. Investigations on the influence of these coupled mechanisms can help to better understand and effectively design geothermal reservoir stimulation techniques, and may also prove useful to explain phenomena that are observed in geothermal fields during the course of reservoir development and long-term exploitation (e.g. induced seismicity and changes in well injectivity with water temperature).

Certain aspects of the thermal and mechanical processes (Ghassemi and Zhang, 2004, 2006) in EGS have already been studied. Also, poroelastic, and thermoelastic mechanisms have been called upon to explain reservoir seismicity (Mossop and Segall, 1994, 1995; Martin and Lowell, 1997; Ghassemi et al., 2005) through their impact on effective stress within subsurface fractures. Chemical reactions between the rock and the circulating fluid have also been studied (Carroll et al., 1998; Johnson et al., 1998; Dobson et al., 2003), and shown to significantly affect fracture aperture by precipitation and dissolution of minerals (Lowell et al., 1993; Bolton et al., 1996; Suresh Kumar and Ghassemi, 2005). However, to date, none of these studies have addressed the combined effects of fluid flow (pressure variation), mass (solute transport), non-isothermal silica transport (reaction kinetics) and thermoelasticity in a fractured rock. Moreover, the influence of both diffusion- and conduction-limited mass and heat transfer between the high-permeability fracture and the low-permeability adjacent rock matrix has not been considered. These phenomena are important because the coupled nature of the fracture–matrix system affects the thermal regime, as well as the rate at which the concentration gradient between the fracture and reservoir matrix influences the opening/closure of the fracture (i.e. the change in fracture aperture and permeability).

The objective of this work is to investigate the individual and combined influences of the thermal and chemical processes on fracture apertures and pressure distributions. This is accomplished by simulating the behavior of the chemically and thermally coupled fracture–matrix system using the code developed by Suresh Kumar and Ghassemi (2005) that is based on the dual porosity concept.

2. Modeling approach

In our study, we only consider pre-existing fractures, not the generation of new ones by thermo-hydraulic stimulation methods. Also, details of the fracture roughness, morphology and fracture density are not taken into account. The hydromechanical behavior of the fracture network is represented by that of a single fracture.