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A coupled thermo-hydro-mechanical modeling of fracture aperture alteration and reservoir deformation during heat extraction from a geothermal reservoir

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ABSTRACT

Hot water extraction and cold water injection into an underground geothermal reservoir cause mechanical deformation of rock matrix and rock joints/fractures. That leads to alteration of hydraulic transmissivity. To study the evolution of reservoir transmissivity we performed coupled Thermo-Hydro-Mechanical (THM) simulations using a robust code called Finite Element for Heat and Mass Transfer (FEHM) for a 3-D domain with a single fracture connecting the injection and production wells. Rock fracture was modeled as a thin equivalent porous medium. We established dynamic relations between the properties of the equivalent porous medium and fracture aperture. In this paper we discuss the alteration of fracture aperture due to heat extraction. The channeling of flow between injection and production wells by THM effects causes faster temperature drawdown and reduces energy production. The model also predicted fracture opening near injection well and closure at far field locations. We also simulated the aperture alteration for different joint stiffness, thermal expansion coefficients and rock matrix permeabilities. Increase in rock matrix permeability not only causes the leakage of injected water but also increases matrix contraction due to cooling and therefore the aperture growth. Additionally we reported the effect of thermo-poro-elastic deformation on the expansion and contraction of the formation for different reservoir properties. We established that in the early-stages the compaction/expansion of the formation was controlled by pore pressure change but in the late-stage it was controlled by thermal contraction.

1. Introduction

Geothermal energy is one of the promising and clean renewable energy resources in the world. Geothermal energy does not depend on the weather conditions and has the potential of providing base load as well as peaking electrical supply. During the last twenty years, application of the geothermal energy for electricity generation, heating and cooling have increased noticeably in many countries, including USA, Iceland, New Zealand and Indonesia. The worldwide installed geothermal power capacity exceeds 12GW (Bertani, 2016). However, total installed capacity is less than 0.5% of the world electric energy generation, with a growth rate of 5.5% per year. Geothermal energy has the potential to provide 3% of electricity and 5% of heating with respect to the global demand by 2050.

The energy is often extracted from underground/subsurface reservoirs by circulating water (cold water is injected and hot water is produced) through a high temperature reservoir. Fractures/joints inside the reservoirs play a pivotal role because they provide dominant flow paths. The transmissivity of a fracture is sensitive to fracture aperture and aperture variations across a range of scales. During energy extraction from a geothermal reservoir the aperture evolution can greatly influence the production temperature (Pandey et al., 2015). Several studies in past have pointed out that the heat extraction rates are very sensitive to operational conditions, i.e., injection temperature (Bedre and Anderson, 2012), flow rate (Franco and Vaccaro, 2014), injection fluid properties (Randolph and Saar, 2011; Shaik et al., 2011; Pan et al., 2015), well spacing (Jain et al., 2015), well placement (Hadgu et al., 2016) and nature of the reservoir such as: reservoir mineral composition (Kiryukhin et al., 2004; Bächler and Kohl, 2005), reservoir hetero-

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geneity (Neuville et al., 2010; Mottaghy et al., 2011; Vogt et al., 2013), reservoir thermal gradient (Garapati et al., 2015), reservoir fluid salinity (Saeid et al., 2015), fracture spacing (Fox et al., 2013; Ekneligoda and Min Ki-Bok, 2014) and fracture geometries (Andrade et al., 2004).

Apart from the above-mentioned factors, reservoir parameters which control the thermo-hydro-mechanical deformation of the reservoir also play important roles in the energy production and lifetime of the geothermal system. The contraction of rock matrix and pore pressure increase during cold water injection into the reservoir can cause significant variation in reservoir porosity and permeability. Past studies have discussed the importance of modeling coupled thermal and hydraulic processes for various geological applications such as geothermal heat extraction (Bruel, 2002; Simone et al., 2013; Kim and Hosseini, 2015), CO_2 sequestrations (Martinez et al., 2013; Dempsey et al., 2014) and nuclear waste disposal (Rutqvist et al., 2009; Tsang et al., 2012). When large fractures/faults/rock joints are the main flow conduits, the modeling of fracture opening and closing (i.e. aperture increase and decrease) are very important for predicting long-term evolution of geothermal reservoirs. Some modeling studies have quantified the coupled THM effects on the single fracture (Kohl et al., 1995; Ghassemi et al., 2008; Zhou et al., 2009; Ghassemi and Zhou, 2011; Rawal and Ghassemi, 2014) and fracture network (Hicks et al., 1996; Koh et al., 2011; Gelet et al., 2012). They demonstrated that cooling and overpressure resulted in reduction of effective normal stresses and increase in fracture aperture. Kohl et al. (1995) performed two-dimensional (2-D) numerical simulation of coupled THM (thermo-hydro-mechanical) processes for flow within a single fracture using a non-linear joint closure law. They found that due to reduction in effective normal stresses the fracture aperture increased, and production rates increased approximately by 25% in 30 years. Hicks et al. (1996) developed 2-D THM model for fracture network in a HDR geothermal reservoir. In their modeling, the reservoir characteristics were taken from the experimental HDR reservoir in the Carnmenellis granite in Cornwall, S. W. England. They showed that injection pressure decreased for THM simulation. They also showed that THM simulations predicted faster decrease of production temperature and reduction of injection pressure. This happened due to increase in fracture permeability as a result of cooling. Koh et al. (2011) studied coupled thermo-hydro-mechanical processes in a discrete fracture network. The fracture closure was modeled as a function of effective stress. Gelet et al. (2012) modeled coupled THM processes in fractured HDR geothermal reservoirs using local thermal non-equilibrium approach. They modeled the reservoir as a dual-porosity medium and their results showed that fracture aperture increased near the injection well due to the contraction of solid and the induced effective stresses were tensile. Simone et al. (2013) investigated hydro-mechanical (i.e., isothermal) and hydro-thermal-mechanical effects of cold water injection in a porous fracture zone-intact rock system. They arrived at the conclusion that rock instability was superposition of hydraulic and thermal effects. They also observed that overall process was very sensitive to the orientation of the fracture, stiffness, stress state regime and confinement conditions. Zhao et al. (2015) performed the coupled THM simulation for Tengchong geothermal field (China). They simulated two large vertical fracture/rock joints connecting the injection and production wells. They found that the fracture aperture increased by a factor of three over nine years of injection/production.

The fluid channelization can occur in EGS operation. In case of fracture networks and variable aperture facture, flow channeling is induced easily due to thermal contraction of rock. This reduces the active volume participating in heat transfer due to confinement of the flow fields and affects the overall performance of geothermal system. The fluid channeling is mainly due to presence of heterogeneities and nonuniform evolution of fracture aperture. Fu et al. (2013) performed a numerical study of coupled thermal–hydrologic–mechanical (THM) processes using discrete fracture network (DFN) model for fracture characterization. They showed that the fracture network characteristics and cooling affected the flow channeling between the wells. Guo et al. (2016) presented coupled thermal-hydrological-mechanical (THM) models to show that spatial heterogeneity played an important role in the evolution of aperture field and flow pattern. They studied the effects of the special correlation length and mean value of aperture field on heat extraction performance. They showed that flow channeling was induced when spatial correlation length was large enough with respect to well spacing, while the effect of heterogeneity was homogenized for small correlation length.

Some of the past studies (Rawal and Ghassemi, 2014; Ghassemi and Kumar, 2007; Taron and Elsworth, 2009; Izadi and Elsworth 2014) also considered the combined thermo mechanical and thermo chemical effects on the evolution of permeability of EGS reservoirs. Rawal and Ghassemi (2014) investigated the aperture change due to coupled thermo-poro-chemo-mechanical processes. They examined the effect of injection temperature, concentration and stiffness heterogeneity in fracture. Their results showed that zones of higher joint normal stiffness aperture were affected less by thermo-poroelastic processes. Ghassemi and Suresh kumar (2007) used a kinetic model of quartz dissolution/precipitation and linear rock joint model for thermal-stress-induced fracture aperture alteration for a simplified geothermal system. They showed that the thermo-elastic effects were significant for entire production life whereas poro-elastic effects were important in the early stage. Taron and Elsworth (2009) proposed a fully coupled THMC model in dual porosity media where the thermal, hydraulic, and chemical (THC) processes were integrated by TOUGHREACT and the mechanical effect was separately solved by using FLAC3D. Izadi and Elsworth (2014) studied the THMC processes in a prototypical enhanced geothermal system (EGS) reservoir. These authors investigated the seismic effects for various fracture network geometries at different depths.

All these studies indicated that couplings among the different physical processes occurred simultaneously. Hence the analysis of coupled processes and feedbacks of thermal, hydrodynamics and mechanical effects on the flow are important for HDR/EGS reservoirs. Significant progresses has been made in the past few decades in hydro-thermal modeling to estimate the energy production rate and life of geothermal reservoirs, however, only a limited number of numerical studies focused on the effect of thermo-hydro-mechanical deformation of rock and fracture on the energy production rate. The effects of various thermal, hydraulic and mechanical properties of the reservoir on the energy production and injectivity alteration were not thoroughly explored. In this study we implemented a nonlinear fracture joint model in FEHM for modeling mechanical deformation of fracture. For modeling aperture alteration of fracture or rock joint, we considered Bandis model of stress dependent fracture stiffness. From that we derived a nonlinear stress-strain relation for the equivalent porous layer to determine permeability alterations. Using this computational model we simulated thermo-hydro-mechanical processes in a 3-D domain, which consisted of a single fracture connecting the injection and production wells. We performed several numerical simulations using different initial joint stiffness, thermal expansion coefficient and permeability of porous rock matrix to study their effects on aperture alteration and heat extraction from geothermal reservoir. The values of the reservoir size, distance between wells, injection conditions, initial fracture aperture and other reservoir parameters were chosen from recent literatures (Pandey et al. 2014, 2015; Kelkar et al., 2014; Rawal and Ghassmi 2014; Guo et al.,