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Investigation of permeability alteration of fractured limestone reservoir due to geothermal heat extraction using three-dimensional thermo-hydro-chemical (THC) model

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ABSTRACT

Heat extraction by cold water circulation disturbs the thermo-chemical equilibrium of a geothermal reservoir, activating the dissolution/precipitation of minerals in the fractures. Calcite being a more reactive mineral than other rock minerals composing the earth curst, we investigate the permeability alteration during geothermal heat production from carbonate reservoirs. In this study the simulations are performed using the code FEHM with coupled thermo-hydro-chemical (THC) capabilities for a three dimensional domain. The computational domain consists of a single fracture connecting the injection and production wells. For reactive alteration of aperture, the model considers that the kinetics of dissolution/precipitation is coupled to the equilibrium interactions among the aqueous species/ions. The reaction rate predominantly depends on the temperature dependent solubility and advective–dispersive solute transport in the fracture. Due to the nonuniform flow fields resulting from injection and production, the coupled thermo-hydro-chemical processes initiate significant variation of the aperture alteration rate over the fracture. We have considered different operating conditions such as different mass injection rate, injection temperature and concentration of minerals. Our simulations show that dissolution and precipitation can occur simultaneously at different locations in fracture. Furthermore the reaction rate varies with time and the reaction rate can also switch between dissolution and precipitation. To illustrate this interesting behavior, the variations of shape and size of zero reaction rate contours with time are shown. An interesting outcome is a non-monotonic evolution of the overall transmissivity between the wells. The alteration of overall transmissivity largely depends on the concentration of mineral in the injected water with respect to the solubility at the initial fracture temperature. For both dissolution and precipitation controlled cases, the rapid changes in transmissivity provide challenges for maintaining circulation of water at constant mass flow rate.

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1. Introduction

The heat energy stored in the deep earth crust known as geothermal energy is an attractive source of energy because it is renewable, clean, and has the potential of providing base load electricity. Geothermal resources are ubiquitous around the world. At present, electricity in excess of 10 GW is commercially produced from naturally occurring hydrothermal waters. An even larger promise is held by hot dry rock (HDR) and enhanced/engineered geothermal systems (EGS), which are estimated to have the potential of supplying an order of magnitude more electrical energy than all hydrothermal power generation systems (Williams et al., 2009). It is estimated that just within the U.S., geothermal energy has the potential of supplying 100 GW electricity by the year 2050 (MIT, 2006).

In geothermal reservoirs the energy is extracted from the underground/subsurface reservoir by circulating water (cold water is injected and hot water is pumped) through fractures/joints in a relatively impermeable reservoir. The heat extraction process depends on coupled thermal, hydraulic, mechanical and chemical (THMC) properties of fractured rock formations. Thus the heat extraction/production involves multiple processes: convection (within the heated fluids), advection (transport of heat, and reactants products by bulk motions of fluids), heat conduction in the rock, molecular diffusion, hydrodynamic dispersion and thermo-poro-elastic deformation of rock. Natural geological reservoirs are complicated geological formations composed of several

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minerals whose physical and chemical properties are generally changed by interaction of hydrothermal fluids with the minerals. Heterogeneities and discontinuities present in the reservoir also add major challenges during exploitation of geothermal resources. In fractured rock systems with low to moderate matrix permeability, the overall permeability is controlled by fractures even though they account for a small fraction of the total porosity. The transmissivity of a single fracture is very sensitive to the fracture aperture and aperture variations across a range of scales. In several geological, energy and engineering contexts, fracture apertures are altered by thermo-hydro-mechanical deformation (Brown and Duchane, 1999; Dempsey et al., 2013; Evans, 2005; Gelet et al., 2012a, 2012b; Ghassemi and Zhou, 2011; Murphy et al., 2004; Rutqvist et al., 2002; Stephansson et al., 1996) and dissolution/precipitation reactions (Andre et al., 2006; Bachler and Kohl, 2005; Chaudhuri et al., 2009, 2012, 2013; Dempsey et al., 2012; Dijk and Berkowitz, 1998; Dobson et al., 2003; Elkhoury et al., 2013; Phillips, 1991; Steefel and Lasaga, 1994; Xu et al., 2004). Fracture transmissivity controls fluid pressures and fluxes, resulting in complex feedbacks. Therefore planning heat extraction from a geothermal system, requires an understanding of the long-term behavior of coupled fluid flow, heat and mass transport and deformation in reservoirs.

The rate of permeability alteration by THC processes depends on mineralogy, reservoir temperature, reaction rates and injection conditions (such as mass flow, injection temperature and concentration of minerals). The influence of geochemistry on different geothermal systems has been considered in several previous works. Jing et al. (2002) studied permeability evolution in hot dry granite reservoir by modeling the 3-D fracture network as an equivalent porous medium. They showed that at higher reservoir temperatures the permeability alteration rate was higher as chemical interactions between water and rock were enhanced. Kiryukhin et al. (2004) numerically simulated thermo-hydro-chemical processes for different geothermal reservoirs in Japan and at Kamchatka, Russia. They observed that the porosity reduction rate varied depending on the mineral composition of the reservoir, temperature, and flow conditions (mass flow rate, single/two phase). Similar observation was also demonstrated by Suresh and Ghassemi (2005) in a dual porosity medium by considering interaction of fluid with quartz. In their study the fracture aperture along the flow field was calculated based on the dissolution/precipitation rate of silica in the fracture. Several other groups of researchers (Andre et al., 2006; Bachler and Kohl, 2005; Rabemanana et al., 2003) studied THC processes related to heat extraction and permeability evolution by dissolution and precipitation in the Soultz-sous-Forêt reservoir as a part of the European Hot Fractured Rock project. These studies examined the effects of interaction of minerals (quartz, K-feldspar, calcite, dolomite, amorphous silica, albite, illite) with hot hyper-saline reservoir brines. The simulation done by Andre et al. (2006), indicated that in the vicinity of the injection well the porosity increased mainly due to dissolution of calcite. Subsequently the dissolved calcite in water precipitated toward the production well, as the calcite is a retrograde soluble mineral. They concluded that the other minerals present in the reservoir (such as quartz, pyrite, dolomite etc.) had less influence on the porosity alteration of the reservoir since their reaction rates were much smaller than calcite. Similar observation was also made by Taron and Elsworth (2009) through numerical simulation. Their results indicated that the dissolution of calcite near the injection well enhanced the permeability by an order of magnitude. On the other hand, for amorphous silica, complete precipitation was encountered over periods of time in excess of 10 years. These studies suggested the significance of reaction rates of different mineral on the evolution of reservoir porosity. Detwiler (2008) experimentally investigated the effect of Damköhler numbers (reaction rate/advection) on mineral dissolution for variable aperture fracture. He found that when reaction rates were much faster than advection, extremely non-uniform dissolution patterns were formed. In this case aperture growth was especially larger near the middle of the fracture. But for lower values of Damköhler number, relatively uniform dissolution occurred throughout the fracture. He also correlated the stiffness of the fracture/joint with dissolution, since mineral dissolution in the fracture reduced the surface contact area leading to increased stress in the remaining contract areas. This study about the change in joint stiffness is important for thermo-hydro-mechanical modeling of reservoirs. There are several other studies (Ghassemi and Suresh, 2007; Ghassemi et al., 2008; Ghassemi and Zhou, 2011; Gelet et al., 2012a,b; Koh et al., 2011; Zhou et al., 2009) which dealt with changes in permeability due to thermal stresses developed at the injection zones. Ghassemi and Zhou (2011) observed that around the injection well, the aperture increased due to combined effect of fluid pressure and normal thermal stress. This caused the overall growth of fracture permeability. The poroelastic, thermoelastic and geochemical effects on aperture evolution usually take place in different time scales. The poroelastic effect is observed starting at short times (hours to days), thermoelastic effects are important for intermediate times (days to months) and chemical effects are important especially for long-time behavior (months to years) (Taron and Elsworth, 2009; Rawal and Ghassemi, 2014). It is clear from the above studies that the long-term permeability change during geothermal heat extraction is influenced by the complex interactions among fluid flow, reaction rates, mineralogy, residence time and other factors. However, detailed quantitative understanding remains to be developed.

Most of the exiting geothermal power plants are located in granite and sandstone, but there are also a few in carbonate formations (Goldscheider et al., 2010). The major exploitation of geothermal energy from carbonate reservoirs are mainly seen in central Europe. In Riehen (Switzerland), the hot water is extracted from the Upper Muschelkalk Limestone aquifer for building heating. The permeability of the reservoir is very high (2×10^{-12} m^2) and the wells are located near the fault boundary of the Upper Rhine Graben (Boissavy and Hauber, 1994). From the production well the water of temperature 66 °C is pumped at a rate of 18 L/s. One of the largest geothermal plants in a limestone reservoir is located at major NNW–SSE striking fault zone, Unterhaching, near Munich in Germany. It has several reinjection and production wells drilled up to more than 3 km depth for thermal energy extraction from upper Jurassic (Malm) limestone underneath Molasse basin and northern foreland basin of Alps. Goldscheider et al. (2010) provided a list of currently operating geothermal power plants in limestone formation established for different commercial purposes such as district heating and electricity generation. They mentioned that the dissolution might have changed the porosity and other properties of these formations but there is no as such studies/reports documenting the geochemical evolution of the carbonate reservoir. They discussed the challenges that arise during the heat mining from several promising provinces in carbonate reservoirs. Retrograde solubility, mixing corrosion and very fast reaction rates compare to sandstone or granite rocks add significant challenges for modeling permeability evolution during geothermal heat extraction from limestone formations. The previous studies (Andre et al., 2006; Bachler and Kohl, 2005; Taron and Elsworth, 2009) on geochemical evolution of silica-dominated reservoirs concluded that calcite is more responsible for porosity/permeability of the reservoir even though the calcite in the reservoir rock is present in a very small fraction (<5%). For carbonate reservoir calcite being the primary mineral, the porosity or aperture is expected to evolve at much faster rate. In this case a more accurate geochemical model comprised of multi-species reactive transport equation is important.

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