Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 92–104

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Coupled hydro-thermo-mechanical modeling of hydraulic fracturing in quasi-brittle rocks using BPM-DEM

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A R T I C L E I N F O

Article history:
Received 22 June 2016
Received in revised form
12 October 2016
Accepted 13 October 2016
Available online 15 November 2016

Keywords:
Hydro-thermo-mechanical (HTM) modeling
Enhanced geothermal systems (EGSs)
Discrete element method (DEM)
Bonded particle model (BPM)
Conductive-convective heat flow and transport
Hydraulic fracturing
Rock permeability enhancement

A B S T R A C T

This paper presents an improved understanding of coupled hydro-thermo-mechanical (HTM) hydraulic fracturing of quasi-brittle rock using the bonded particle model (BPM) within the discrete element method (DEM). BPM has been recently extended by the authors to account for coupled convective–conductive heat flow and transport, and to enable full hydro-thermal fluid–solid coupled modeling. The application of the work is on enhanced geothermal systems (EGSs), and hydraulic fracturing of hot dry rock (HDR) is studied in terms of the impact of temperature difference between rock and a flowing fracturing fluid. Micro-mechanical investigation of temperature and fracturing fluid effects on hydraulic fracturing damage in rocks is presented. It was found that fracture is shorter with pronounced secondary microcracking along the main fracture for the case when the convective–conductive thermal heat exchange is considered. First, the convection heat exchange during low-viscosity fluid infiltration in permeable rock around the wellbore causes significant rock cooling, where a finger-like fluid infiltration was observed. Second, fluid infiltration inhibits pressure rise during pumping and delays fracture initiation and propagation. Additionally, thermal damage occurs in the whole area around the wellbore due to rock cooling and cold fluid infiltration. The size of a damaged area around the wellbore increases with decreasing fluid dynamic viscosity. Fluid and rock compressibility ratio was found to have significant effect on the fracture propagation velocity.

1. Introduction

This paper investigates the dynamic coupled hydro-thermo-mechanical (HTM) processes in rocks during hydraulic fracturing for geothermal reservoir creation as a means for extracting heat from deep hot rock formations with low permeability, lack of fluid or both in enhanced geothermal systems (EGSs). Steam is produced by injecting cold water from the ground surface through wells into the hot fractured rock, where injected water exchanges heat with hot rock and turns into the steam. The steam flows up via production wells to the electric power plant for energy production (Economides et al., 2000). Prior to the production, hydraulic fracturing is used to enhance permeability of the reservoir rock, which is typically crystalline (e.g. granite) that has permeability lower than 10^{-3} μD (Clark, 1949). One of the challenges, which prevents successful hydraulic fracturing of EGS reservoir in practice, is understanding how the temperature difference between fracturing fluid and hot rock mass affects hydraulic fracture initiation and propagation. Geothermal reservoirs are characterized by abnormally high temperatures which may exceed 250 °C. For example, at the 2.75 km depth of the reservoir in the Jemez Mountains of northern New Mexico, USA, the temperature is 185 °C (Grigsby et al., 1983), while the fracturing fluid enters the injection well at room temperature and then heats up to about 56–60 °C in the production well.

Reservoir in situ stresses can also be very high in geothermal rock formations. For instance, in the 2-km deep Rosemanowes hot dry rock (HDR) test site in Cornwall, UK, the in situ vertical stress is approximately 70 MPa, and the minimum in situ horizontal stress is 30 MPa (Pine et al., 1983). Borehole cooling causes stress changes around the wellbore, which are expected to be important in the hydraulic fracturing process. A study of heat extraction from geothermal reservoirs shows that thermal stress cracking can occur

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2016.10.001

in injection wells (Murphy, 1978). Additionally, reservoir rock mechanical properties are usually temperature-dependent (Heuze, 1983). For temperatures of up to 300 °C in EGS, the Young's modulus, tensile strength, cohesion and friction angle can be 80% lower than those at room temperature (Heuze, 1983). Wang et al. (1989) performed laboratory testing of granite under high temperatures up to 300 °C and confining pressures up to 55 MPa with the goal of better understanding thermal cracking in granite. Their observations reveal that significant thermal cracking occurs when granite is heated above 200 °C at 28 MPa and above 100 °C at 7 MPa. The majority of the created thermal cracks closed at confining pressure of 40 MPa. Grain boundaries between quartz grains and between quartz and other minerals were preferentially cracked as observed using scanning electron microscope.

Experiments in crystalline rock have shown that the temperature, heating and cooling rates, thermal gradients, thermal history and mineralogy can affect the intensity and characteristics of the thermally-induced microcracks (Kranz, 1983). Significant microcracking begins above a threshold temperature of about 70–75 °C for granite. However, the threshold temperature is sensitive to the thermal history, and consequentially, the new microcracking begins after the previous maximum temperature has been surpassed (Johnson et al., 1978; Yong and Wang, 1980). Bauer and Johnson (1979) observed that most thermally-induced cracks in feldspars and granites were cleavage cracks. Pre-existing cracks formed at lower temperatures became larger at higher temperatures (Bauer and Johnson, 1979). The amount of quartz has a significant effect on thermally-induced microcracking because of its large and anisotropic coefficient of thermal expansion. The differential thermal expansion between quartz and feldspar grains plays a dominant role in producing cracks in granite (Kranz, 1983). Differential contraction upon cooling also produces cracks in rock, but the quartz remained un-cracked (Stout, 1974). Thermally-induced microcracks occur primarily through differential and incompatible thermal expansion or contraction between grains with different thermoelastic moduli, or between similar misaligned anisotropic grains. Thermally-induced microcracking can be initiated within individual grains at internal boundaries under thermal gradients. The growth direction of a thermally-induced intra-crystalline crack depends on the relative magnitudes of the thermal expansion coefficients (Bruner, 1979). Crack growth velocities as low as 10^{-7} cm/s have been measured in rocks and rock minerals (Atkinson, 1979). The upper bound of fracture propagation in rocks is the terminal velocity, which is experimentally obtained for brittle rock at 1800 m/s (Bieniawski, 1967). Hydraulic fracture velocity depends, however, on fluid and rock properties. In spite of the fact that a large amount of work has been done on fracture propagation in rocks due to different loadings, the hydraulic fracture propagation has not yet been fully understood. Cracks can be significantly influenced by thermal stresses below velocities of about 1 cm/s, where the crack propagation is called "subcritical" and the growth of cracks, primarily in silicates, is attributed to stress-aided corrosion processes at the crack tip (Kranz, 1983). Controversially, it was also found that thermally-induced stresses are sometimes not sufficient to cause microcracking under high confining pressure (Wong and Brace, 1979; van der Molen, 1981). Zhao (2016) briefly reviewed the temperature-dependent mechanical properties of various rocks and investigated thermal influence of microcracking on mechanical properties of granite. Both cycling and monotonous heating of the specimen yielded reduction of tensile and compressive strengths of crystalline rocks through thermally-induced microcracks.

Modeling efforts, which have been previously proposed for addressing convective and conductive fluid and heat flow through fractured and porous media, have primarily used macro-scale continuum approaches. These include: (1) volume averaging (effective continuum, double porosity, dual permeability and multiple interacting continua (MINC) models) that are well suited for representing larger-scale fractured rocks (Pruess, 1985; Pruess et al., 1999; Spycher and Pruess, 2010); (2) models based on stochastic theories for addressing irregularities of natural-sediment property distributions (Faybishenko et al., 2005); (3) continuous-time random-walk (CTRW) models (Berkowitz and Scher, 2001; Bogdanov et al., 2003; Singurindy and Berkowitz, 2003; Adler et al., 2005; Berkowitz et al., 2006); (4) coupled finite-volume and distinct fracture network (DFN) multiphase flow models which include thermodynamic regime with phase change for fluid and heat conduction (Pruess, 1985); and (5) distinct element codes for fractured rocks which combine convective–conductive thermal and mechanical coupling (Itasca, 1992; Abdallah et al., 1995).

Previous modeling efforts on coupled HTM processes in geothermal reservoirs have addressed important issues but the knowledge is still limited for providing a complete understanding of how cracks and fractures initiate and propagate due to fluid pressure and temperature changes in geothermal reservoirs. Particularly, the effects of convective heat flow during fracturing fluid infiltration into the rock adjacent to the wellbore have not yet been addressed. The microscale damage caused by thermal stresses along the fracture and around the wellbore and its influence on hydraulic fracture initiation and propagation are not well understood. Discrete element method (DEM) modeling was also used because it has several advantages over widely used finite element methods (FEMs). Particularly, FEM deals with fracture problems by activation of pre-existing weakness planes in the model, which requires computationally expensive remeshing. Therefore, naturally occurring tortuous fractures are hard to model, and the free occurrence of new fractures in random directions is difficult to predict. FEM does not allow formation of new free surfaces or random microcracks. The advantage of DEM is the ability to directly capture and model fracture and microcrack evolution through a synthetic rock mass model. At the same time, for modeling fluid flow in fractured rock masses, where the fluid initially has different temperatures compared to rock, it is crucial to be able to implement the full transient convective–conductive heat behavior of both fluid and rock. However, existing DEM codes like the particle flow code (Potyondy and Cundall, 2004) can only model thermal conduction. To address this deficiency, Tomac and Gutierrez (2015) have recently developed a DEM model which can correctly capture the phenomena of convective heat exchange between rock and fluid. The objective of this paper is to implement this modified DEM-BPM (bonded particle model) in coupled HTM modeling, and apply it to the study of the micro-mechanics of hydro-thermal cracking and fracturing in EGS reservoir rocks. The results of this work can be directly employed not only for geothermal applications but also for underground coal gasification.

2. Methodology

2.1. Discrete element method (DEM) with bonded particle model (BPM)

DEM has been used in numerical modeling for particulate media interactions for over three decades (Cundall and Strack, 1979). DEM uses an explicit finite difference scheme for solving the trajectories of individual particles in a particulate system. Forces applied to particle centers come from interactions with neighboring particles at particle contacts, walls or volume forces. Particle-to-particle interactions are modeled via spring and damper elements parallel and normal to the particle contacts. The BPM, formulated by Potyondy and Cundall (2004), is used in this study. The BPM is integrated within the two-dimensional (2D) particle flow code (PFC^{2D}) developed by Itasca (2004). BPM enhances the DEM capability from