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Micromechanics of hydro-thermal damage and fracturing in rocks based on DEM modeling with thermal convection

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1 INTRODUCTION

Improved understanding of the fundamental coupled hydro-thermo-mechanical (HTM) processes in porous and fractured rocks, particularly those that lead to damage and fracturing, are important in different fields such as enhanced geothermal systems (EGS), CO_2 geological sequestration, oil and gas production, and contaminant and nuclear waste disposal and storage. Fluid injection and extraction in geo-reservoirs will lead to significant pore pressure and temperature changes resulting in induced variations in the spatial and temporal mechanical state of the rock mass. The fundamental HTM processes in the rock are fully coupled (Gutierrez & Lewis 2002). First, fluid flow affects pores pressures and temperature. Secondly, fluid pressure and temperature changes will induce rock mechanical response. Thirdly, and in turn, rock mechanical response can affect fluid pressures and permeability of the rock mass. The most dramatic effect of pore pressure and temperature changes in rocks is when they result in significant stress changes that can induce damage and fracturing with repercussions to long-term geo-reservoir behavior. The processes of mechanical damage and fracturing have micromechanical origins that often occur at the grain-to-grain contacts and must be investigated micro-mechanically.

Two aspects of the coupled HTM behavior of rock masses that have not been fully addressed are: (1) the micromechanical origins of damage and fracture in rocks, and (2) the influence of heat transfer due to thermal convection induced by fluid flow. Micro-mechanical modeling using the Discrete Element Method (DEM) as implemented in the computer code *PFC* (Itasca 2004) can enable a better understanding of the damage and fracturing of rocks. DEM dynamically updates rock permeability at the microscale due to rock deformations from stress, pore pressure and temperature changes. In turn, fluid and heat flow dynamically adjust because of mechanical changes in the micro-structure of the rock. One deficiency of DEM models for HTM processes is the inability to model fluid-flow induced convective heat transfer as they only account for thermal conduction. At the micro- and macroscopic levels, it is expected that fluid-flow-induced convective temperature changes in the pores will dominate the conductive heat flow from grain to grain. Modeling convective-conductive heat flow and transport in rocks is complicated due to the extremely different length scales of both processes. DEM has only been recently improved by the introduction of convective heat transport for simulating transient heat energy exchange between pore fluid in motion and rock by Tomac & Gutierrez (2015) in *PFC*.

This paper addresses knowledge gaps related to the conditions which lead to development of hydro-thermal damage zones and fracturing in brittle rocks due to both pore pressure and conductive-convective temperature changes in geo-reservoirs. Micromechanical understanding is improved through DEM, which spatially discretizes the rock mass into discrete particles that interact at their contacts and can explicitly model fracture propagation and micro-crack type damage at the grain scale. In this study, the DEM mechanical model is coupled with solvers for porous media fluid flow and heat flow/transport to model the coupled HTM processes responsible for damage and fracturing. Coupled HTM in DEM models fluid flow through the newly formed hydraulic fractures and changes in pore pressure. The stress-strain response of the DEM model is calibrated against previously published experimental data on rocks under different loading rates. The main objective of this study is to understand how rock pore pressure, temperature and stress-strain evolutions lead to rock damage and fracturing at the micro to macro-scale. Better understanding of processes involved can lead to well-controlled fracture propagation and more efficient hydraulic fracturing operations through managed fracture tip processes, damage and fracture branching.

2 DEM FOR COUPLED MODELING OF HYDRO-THERMAL DAMAGE AND FRACTURING IN ROCKS

The coupled DEM HTM model used in this paper is based on *PFC2D* with two major modifications: (1) the Bonded Particle Model (BPM) of Potyondy & Cundall (2004) to simulate intact cohesive-frictional rock behavior, and (2) the extension of the heat conduction model in *PFC2D* by Tomac & Gutierrez (2015) to account for heat convection due to a moving pore fluid with different temperature from the rock matrix. The mechanical behavior of the model of synthetic porous rock matrix is coupled with explicit transient Newtonian fluid flow through deformable rock matrix or designated channels and heat flow and transport. BPM enhances the DEM capability from modeling granular assembles towards cohesive-frictional porous materials. In BPM, particles are bonded together with parallel bonds which can be pictured as cementation at the particle contacts for transferring forces or bending moments and area assigned with normal and shear stiffnesses. As a result, a solid comprised of bonded particles can be assembled. The main advantage of BPM is that fracturing can also be directly observed when the bond between particles is broken under local stress tensor that exceeds the bond strength.

The combined heat flow and transport model aims to capture the complete thermal energy migration (without radiation) through permeable solid filled with flowing fluid with initially non-uniform thermal distribution. The built-in heat conduction model in *PFC* defines the transient flow of thermal energy through the model from initially non-uniform spatial distribution. This built-in model has been extended to account for thermal convection. The combined convective-conductive heat flow and transport is formulated using lumped capacitance method which includes the justification of the local equilibrium assumption. Heat conduction for a continuum follows Fourier's law that describes the relation between the heat-flux vector and the temperature gradient. For thermal convection, heat exchange between solid phase and fluid in channels occurs simultaneously with fluid flow driven by pressure gradients in fluid channels which exist between particles. Parallel-plate flow solution is introduced in the numerical scheme for fluid and heat flow at a fluid channel.

For hydro-thermo-mechanical coupling, the stress tensor of the DEM assembly spatially evolves during the time-stepping procedure. Stress changes consist of mechanical, hydraulic and thermal components. Pore pressure changes affect the effective stresses, which governs the mechanical behavior through the effective stress law. The thermal stresses are consequence of temperature-induced strains, which, arise due to thermal volumetric deformation of particles. In turn, the bond length between particles in contact resulting in change in the contact normal force vector between the two particles. results and discussion

3 RESULTS AND DISCUSSION

This study presents uncovered new results the micromechanical effects of pore pressure and temperature differences between fracturing fluid and rock during hydraulic fracture initiation and propagation. Figure 1 shows two examples of fracture propagation in initially impermeable rock without thermal effects (Fig. 1a) and with thermal effects (Fig. 1b & c), where the temperature difference ΔT between fracturing fluid at the borehole and rock is 150°C. In the middle of Figure 1a, a single fracture is shown propagating in the direction of maximum compressive stress in the biaxially compressed model. Dry fracture tip is a well-known phenomenon and is shown as interconnected blue lines (broken tensile parallel bonds in DEM). Fluid (covered with cyan circles) infiltrated part of the fracture and follows behind the dry fracture tip. Figure 1b and c shows the results of simulation under boundary and initial conditions same as Figure 1a, except for the temperature difference. First, the thermo-mechanical fracture is shorter than the mechanical one, and with evidence of micro-damage and microcracks shown with blue lines. Consequently, the cracking and damage are caused by thermal stresses, as seen in zoomed detail in Figure 1c. Thermal flux vectors are visible as black arrows. Observation that the thermo-mechanically-induced fracture is wider than the mechanical one, is obtained from the larger number of parallel microcracks (blue lines) next to each other and several parallel fluid flow reservoirs filled with fluid (cyan circles). Second, the fractured area near the wellbore, where cold fluid enters the hot rock, is wider than that in Figure 1a with interconnected broken bonds which branch out perpendicular to the main fracture direction. As a result, fluid also infiltrates this cracked area demonstrated via several cyan pressure circles next to each other. Third, the dry fracture tip is still present, but it branches into three directions. Figure 1 shows clear effects of micro-mechanical thermal effects on fracture initiation, propagation and related damage mechanisms. Convective-conductive coupling of heat flow and transport and mechanical fracturing process is evident through observation of secondary microcracks located at areas of large heat flux vectors.

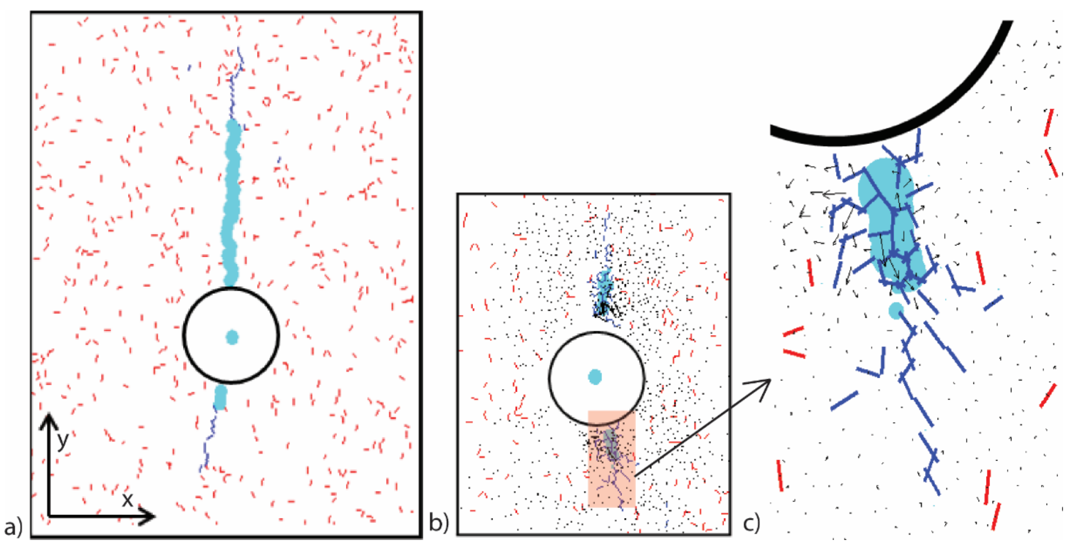

Figure 1. Fracture propagation in impermeable rock for: (a) ΔT=0 °C and (b) ΔT=150 °C, in a DEM model of 30 cm × 60 cm in dimensions, with 4 cm borehole diameter under far-field confinement stresses $\sigma_{\max,y}$=10 MPa and $\sigma_{\min,x}$=6 MPa, where fluid pressure P_b=16 MPa. Black arrows are heat flux vectors, cyan circles are fluid reservoir pressures, blue lines are tensile microcracks, and red lines are shear microcracks.

4 CONCLUSIONS

This paper investigated the development of hydro-thermal damage zones and fracturing in brittle rocks due to both pore pressure and conductive-convective temperature changes in geo-reservoirs. The results showed significant effects of temperature difference between hot rock mass and colder fracturing fluid on fracture initiation and propagation. Thermal stresses caused microcracks along the propagating fracture, which permit fluid infiltration into the rock near the fracture surface and, as a result, further micro fracturing had occurred. By comparing hydraulic fracturing without fluid and rock temperature difference with the one with thermal effects, several new insights were found. First, the thermo-mechanical fracture is shorter than mechanical one, and with evidence of microdamage and microcracks which were caused by thermal stress. Second, the fractured area near the wellbore, where cold fluid enters the hot rock, is wider with interconnected broken bonds which branch out perpendicular to the main fracture direction. Third, the dry fracture tip is still present, but it branches into several directions. Infiltration of cold fluid into hot rock adjacent to the main fracture was observed here to not significantly affect the principal stresses orientation.

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