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Microscopic numerical modeling of Thermo-Hydro-Mechanical mechanisms in fluid injection process in unconsolidated formation

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ABSTRACT

The temperature difference between injected fluid and surrounding rock can play an important role in the initiation and propagation of fractures in completion and simulation operations. In this work, the thermal effect is investigated using DEM-based micromechanics model implemented in Particle Flow Code (PFC). The rock mass is represented by an assembly of discrete particles that are bonded at contacts. In the developed thermo-hydro-mechanical (THM) module, heat conduction across the solids in the rock matrix and heat convection between the injected fluid and solid particles are coupled. The evolution of the system is driven by a continuous point source of heat. Simulation results show that more cracks tend to be generated in anisotropic thermal conductivity, and the thermal induced stress, temperature distribution and pore pressure predicted by this model are consistent with laboratory observations and simulation results from conventional continuum mechanics models. Furthermore, the Fracability Index is introduced for evaluating the fracturing performance, in the comparison between hydro-injection and hydro-thermal injection (heating and cooling). This study indicates that thermal stresses can greatly affect initiation and propagation of fractures and assist the communication between injection pressure and pore pressure in the rock formation; thermal fracturing can be considered as an effective method to connect fracture network, enhance weak zones and create more fractures.

1. Introduction

In Enhanced Geothermal System (EGS), underground heat can be extracted and exploited by injecting and circulating fluid to create fractures. A significant temperature difference between the wellbore fluid and rock formation introduces additional compressive or tensile stresses, depending on whether the fluid temperature is higher or lower than the surrounding rock (Zoback, 2007). Most existing research works related to thermal stresses have been focusing on the geothermal and fractured reservoirs. For example, thermal and mechanical coupled processes of thermal cracking and heat extraction are investigated in EGS (Ghassemi et al., 2005; Ghassemi and Zhang, 2006). Zeng et al. (2013) investigated the potential of heat production from deep hot dry rock and indicated that produced heat relies on thermal conductivity, injection temperature and water production rate. In a fractured reservoir, the heat flow within the fracture is primarily accomplished by advection; in the area outside the fractured zone, heat flow is mainly controlled by conduction (Mossap, 2001).

The investigation of Thermo-Hydro-Mechanical (THM) process in fractured reservoir has been developed rapidly in recent years. Both numerical simulations and laboratory experiments showed that cooling injection is an effective approach to improve reservoir permeability. Three-dimensional structural model showed that rock shrinkage will very likely take place after several months of cooling circulation and the tractions across fractures around re-injection borehole can significantly increase (Bruel, 2002). A 3D thermal model is developed and coupled with a pseudo three-dimensional (P3D) fracture propagation model (Amini et al., 2015). This model could be used to interpret Distributed Temperature Sensing (DTS) data that can provide wellbore temperature profile. The laboratory studies showed that a strong thermal gradient is generated by increasing the number of cryogenic stimulation after injecting liquid nitrogen (LN_2). The fracturing can be enhanced as a result of creating new cracks and reactivating/opening pre-existing cracks. In addition, this method avoids the shortcomings of water-based hydraulic fracturing, such as formation damage, water supply shortage, and contentious political climate (Cha et al., 2014).

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Some studies have attributed seismic events to the occurrence of thermal stresses. De Simone et al. (2013) suggested that decreasing temperature induces a significant perturbation on the stress field even in an intact rock. The changes of fracture aperture also give a distinctive response to thermal stress (Ghassemi and Suresh Kumar, 2007; Jalali et al., 2015). However, there is little or very limited in-depth investigation concentrating on stress variations and distributions due to rock contraction or expansion and associated cracking propagation using Distinct Element Method (DEM).

In this study, a THM model implemented in DEM-based micromechanics software PFC is employed to investigate the thermal effects in the fluid injection in the unconsolidated sandstone. In comparison with the conventional continuum mechanics methodologies used in most existing studies, micromechanics approach is more powerful in revealing fundamental mechanisms underlying the modeled mechanical and physical processes. The drawback is that it is much more computationally extensive and even becomes prohibitive when modeling large scale problems. In the modeling work presented in the following sections, heat conduction in solid matrix and heat convection between fluid flow and surface of solid particles are simulated independently and also coupled. Fluid injection under various scenarios is modeled in a series of simulations. The evolution of stress, temperature, pore pressure, initiation and propagation of fractures are tracked and analyzed.

2. Heat conduction in PFC modeling

In PFC (Itasca, 2008), the heat conduction between particles is the primary mode of heat transfer in the simulation of thermal process. The particles and the corresponding contacts are associated with network of heat reservoirs and connecting thermal pipes representing thermal transfer characteristics of rock mass. Fig. 1 shows that in the particle system, the conduction of heat flow takes place in the active thermal pipes when the contact bond is present or there is overlap between two particles at contact. The red cylindrical particles 1, 2 and 3 are the particles of heat source or heat reservoir, the purple cylindrical particle 4 is the one that receives the heat from the contacting particles 1, 2, 3; the blue arrows denote the direction of heat conduction through thermal contacts; for example, from source heat particle 1, the direction of thermal conduction is normal to the tangent line between particle 1 and 4. The variation of the number of active thermal pipes is affected by loading or damage to the rock, resulting in form or breakage of bonds.

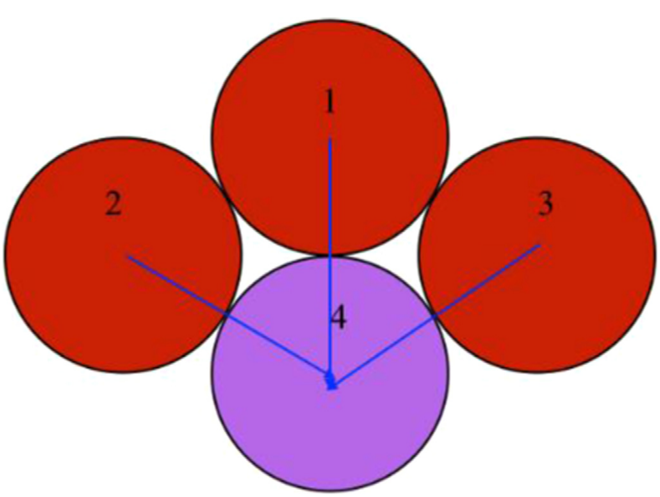

Fig. 1. Heat transfer between solid particles via active thermal pipes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The power in a thermal pipe model is governed by (Itasca, 2008):

$$Q = -\frac{\Delta T}{\eta L} \tag{1}$$

where ΔT is the temperature difference between the two reservoirs at the ends of a thermal pipe, and L is the thermal pipe length, and η is the thermal resistance per unit length.

The differential equation of heat conduction is derived from substitution of Fourier's law into the continuity equation, which can be applied to simulate transient heat conduction and storage in particle system.

The Fourier's law describes the relation between the heat transfer rate and the temperature gradient in the heat conduction process:

$$q_i = -k_{ij}\frac{\partial T}{\partial x_j} \tag{2}$$

where q_i is the heat-flux vector in unit of W/m^2; k_{ij} is the thermal conductivity tensor in unit of W/m °C and T is the temperature in unit of °C.

Thermal expansion of the particles and parallel bonds at contacts can be accounted for by the developed thermal strains. For a change of temperature ΔT, the corresponding increment of particle radius is:

$$\Delta R = \alpha R \Delta T \tag{3}$$

where α is the coefficient of linear thermal expansion, in the unit of 1/°C; it is a micro property associated with the particle material. The other thermal micro-properties used in PFC are: each particle's density, ρ, with unit of kg/m^3; specific heat constant volume, C_v, with unit of J/kg °C; and thermal resistance per unit length, η, with unit of °C/W .

For particle bond expansion, we assume that it is only the normal component of the force vector carried by the bond that will be affected by the change of temperature. The relationship between the present parallel bond and active thermal pipe is:

$$\Delta \bar{F}^n = -\bar{k}^n A \Delta U^n = -\bar{k}^n A\left(\bar{a}\bar{L}\Delta T\right) \tag{4}$$

where $\bar{k}^n$ is the bond normal stiffness, A is the area of the bond cross-section, $\bar{a}$ is the expansion coefficient of bond material, $\bar{L}$ is the bond length, ΔT is the temperature increment, which equals to

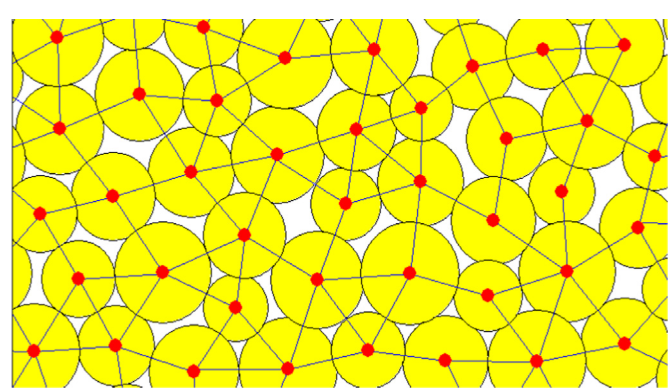

Fig. 2. Heat conduction in particle thermal system in PFC^{2D}: yellow disks are particles; blue lines passing through contact point or tangent point of two circular particles are thermal pipes; red dots are heat source. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)