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A three-dimensional coupled thermo-hydro-mechanical model for deformable fractured geothermal systems

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ABSTRACT

A fully coupled thermal-hydraulic-mechanical (THM) finite element model is presented for fractured geothermal reservoirs. Fractures are modelled as surface discontinuities within a three-dimensional matrix. Non-isothermal flow through the rock matrix and fractures are defined and coupled to a mechanical deformation model. A robust contact model is utilised to resolve the contact tractions between opposing fracture surfaces under THM loadings. A numerical model has been developed using the standard Galerkin method. Quadratic tetrahedral and triangular elements are used for spatial discretisation. The model has been validated against several analytical solutions, and applied to study the effects of the deformable fractures on the injection of cold water in fractured geothermal systems.

Results show that the creation of flow channelling due to the thermal volumetric contraction of the rock matrix is very likely. The fluid exchanges heat with the rock matrix, which results in cooling down of the matrix, and subsequent volumetric deformation. The cooling down of the rock matrix around a fracture reduces the contact stress on the fracture surfaces, and increases the fracture aperture. Stress redistribution reduces the aperture, as the area with lower contact stress on the fracture expands. Stress redistribution reduces the likelihood of fracture propagation under pure opening mode, while the expansion of the area with lower contact stress may increase the likelihood of shear fracturing.

1. Introduction

Energy extraction from geothermal reservoirs involves multiple physical processes including thermal (T), hydro (H), and mechanical (M) processes that together influence the heat extraction from fractured geothermal systems (Tsang, 1991; MIT, 2006). Due to the complexity of this problem, and the number of parameters involved, modelling of these systems is viable primarily through numerical methods (McDermott et al., 2006). In a geothermal system, cold fluid is injected into an injection well, and hot fluid is extracted from the production well (e.g., Crooijmans et al., 2016). In order to understand the coupled processes and their effects, a robust numerical model that simultaneously solves all the governing equations in a coupled manner is essential for the successful investigation of a fractured geothermal system.

Fractures, natural or man-made, enhance flow within geothermal reservoirs. For instance, fractures dominate the flow in low permeability hot dry rocks (HDR) in the subsurface. Fractures may also contribute to the creation of short-circuits between injector and producer wells, hence reducing the efficiency of a geothermal system (Emmermann and Lauterjung, 1997). In enhanced geothermal systems (EGS), due to the low permeability of the host rock, artificial fractures are induced, prior to injection of cold fluid, in order to enhance the effective permeability of the hot rock. In EGS, the stimulation can occur through induced slip on pre-existing fractures (shear stimulation), by creating new fractures using hydraulic fracturing technique (opening mode), or by a combination of the two (McClure and Horne, 2014). Thermally-induced fracturing has also been frequently observed in many subsurface applications, where a relatively cold fluid has been injected into a reservoir: for instance, in water injection wells in the petroleum industry (Bellarby, 2009), in geothermal wells (Benson et al., 1987; Tulinius et al., 2000), and even in relatively soft, unconsolidated formations (Santarelli et al., 2008). The volumetric flow rate in a fracture is proportional to the pressure gradient and the cube of the fracture aperture, i.e., the cubic law, which is derived from the general Navier-Stokes equation for flow of a fluid between two parallel plates (Zimmerman and Bodvarsson, 1996). Thus, variation in fracture aperture due to the changes in the normal and/or shear stresses acting on the fracture surfaces as a result of the THM processes strongly affects the fluid flow and heat transport in the fracture (Rutqvist et al., 2005).

Heat conduction between the fluid inside the fracture and the

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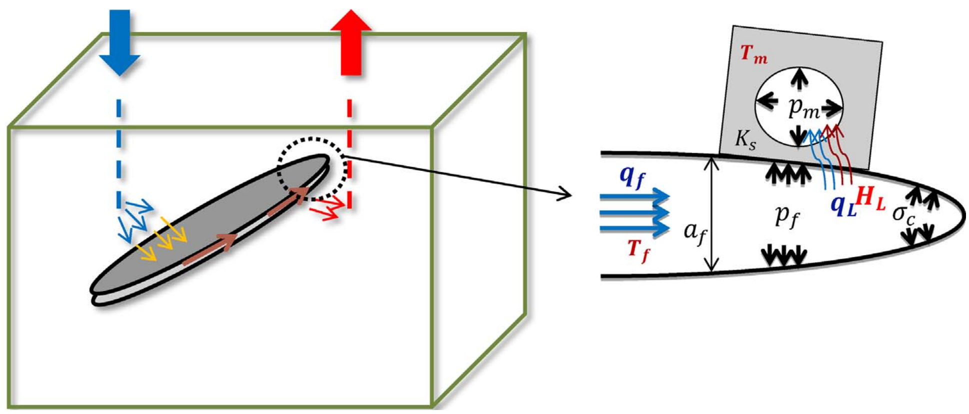

Fig. 1. Schematic representation of a fractured geothermal doublet.

surrounding rock matrix has been of particular interest in many situations, including magma-driven fractures (Spence and Turcotte, 1985), hydraulic fracturing of wells (Wang and Papamichos, 1999), and hydraulic fracturing of shale gas reservoirs (Tran et al., 2013; Enayatpour and Patzek, 2013; Salimzadeh et al., 2016). Rock temperature at the surfaces of the hydraulic fracture is often considered constant, and equal to the temperature of the injected fluid (for example in Tran et al., 2013; Abousleiman et al., 2014). However, such an assumption does not satisfy conservation of energy, and does not account for the fact that heat exchange between the fracturing fluid and the rock gradually causes the fracturing fluid to thermally equilibrate with the matrix rock. Consequently, an unrealistically large effect due to thermal non-equilibrium is predicted by such approaches (Salimzadeh et al., 2016). Considerable efforts have been expended in developing THM models for geothermal reservoirs over the past several decades; however, very few studies have taken into account the evolution of fracture permeability under thermoporoelastic effects. McDermott et al. (2006) investigated the influence of THM coupling on the heat extraction from reservoir in crystalline rocks using an experimentally validated geomechanical model. Ghassemi et al. (2008), using a partially coupled formulation, derived analytic solutions for calculating fracture aperture changes induced by thermoelastic and poroelastic stresses during cold-water injection in an enhanced geothermal system (EGS). Ghassemi and Zhou (2011) proposed an approach to couple fracture flow and heat transport to thermoporoelastic deformation of the rock matrix using the displacement discontinuity (DD) method in which coupling is realised sequentially. Sequential coupling, in a non-linear system, suffers convergence problems, and requires more iteration and manual interference to converge. Abu Aisha et al. (2016) investigated the effects of the new fractures created during a geothermal lifetime on the overall permeability tensor of the fractured medium. Pandey et al. (2017) proposed a coupled THM model for the variation of fracture aperture during heat extraction from a geothermal reservoir. They treated a fracture as a thin permeable layer in the matrix, with a stress-dependant fracture stiffness and elastic modulus. Guo et al. (2016) investigated the effect of the heterogeneity in the initial aperture distribution on the flow path within a single fracture in an EGS. The equivalent permeability in fractured reservoirs can be significantly affected by the choice of the aperture distribution model (Bisdom et al., 2016).

In the present study, a finite element model is presented in which fractures are treated more accurately in terms of their representation in the mesh, as well as in their physical behaviour under THM loading. Fractures are modelled as 2D surface discontinuities in the 3D rock matrix. Separate but coupled flow/heat models are defined for the fracture and the rock matrix. The flow through the fractures is governed by the cubic law, and is coupled to the Darcy flow in rock matrix using leakoff mass exchange that is computed as a function of the fracture and matrix fluid pressures, and the matrix permeability. Local thermal non-equilibrium is considered between fluid in the fracture and fluid in the rock matrix. Advective-diffusive heat transfer is assumed in both the fractures and rock matrix. Heat transfer between fracture and matrix is allowed by conduction through the fracture walls, as well as by advection through the leakoff flow. Contact stresses on the fracture surfaces are computed using a robust contact model. Thermal and hydraulic loadings are considered in computing the contact stresses. The contact model is iteratively coupled to the THM model. The governing equations are solved numerically using the finite element approach. The coupled model has been validated against several available solutions, and applied to investigate the effects of fracture aperture alteration due to THM processes on the flow of the cold fluid in geothermal reservoirs.

2. Computational model

The fully coupled computational model is constructed from five separate yet interacting sub-models: a thermoelastic deformation model, two flow models (one for the fractures and one for the rock matrix), and two heat transfer models, for fracture and rock matrix, respectively. Single-phase flow is assumed within both the fractures and the rock matrix. In the thermoelastic mechanical model, the flow and the heat transfer through the rock matrix are constructed for three-dimensional matrix body, while flow and heat transfer models through the fractures are defined for two-dimensional discrete fractures, as schematically shown in Fig. 1. Fracture flow and solid deformation are two-way coupled through hydraulic loading exerted on the fracture surfaces, as well as by ensuring the compatibility of fracture volumetric strains. Heat transfer in the rock matrix and fractures is also coupled through a heat exchange term included in the fracture and matrix energy balance equations. A displacement vector (three components), fluid pressures (two components), fracture fluid and matrix temperatures (two components) are defined as primary variables. Tension is reckoned positive for stresses in the governing equations.

2.1. Thermoporoelastic mechanical model

The thermoporoelastic mechanical model is based on the condition of stress equilibrium for a representative elementary volume of the porous medium. The assumption of elastic behaviour for matrix deformation is reasonable for most thermally-induced rock deformations (Rutqvist et al., 2005). For quasi-static conditions, the linear momentum balance equation for this elementary volume may be written as

$$\mathrm{div}\,\boldsymbol{\sigma} + \mathrm{F} = 0 \tag{1}$$

where **F** is the body force per unit volume, and $\boldsymbol{\sigma}$ is the total stress. Effective stress is defined as the function of total stress and matrix pressure that controls the mechanical effects of a change in stress. It is defined exclusively within the rock matrix, linking a change in stress to the change in strain. The effective stress for the rock matrix saturated with a single-phase fluid is defined as (Biot, 1941)