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Research Paper

Evaluation of geothermal development in fractured hot dry rock based on three dimensional unified pipe-network method

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HIGHLIGHTS

- 3D UPM is developed for modeling the thermal-hydro (T-H) coupling process in EGS.
- An adaptive conforming mesh method is employed to discrete the matrix and fractures.
- The LTNE theory is incorporated to simulate the geothermal development with fracture networks.

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ABSTRACT

Understanding the subsurface heat transmission together with thermal-hydro (T-H) coupling process in fractured rock mass is essential to the heat mining from enhanced geothermal systems (EGS). A three dimensional numerical model based on a unified pipe-network method (UPM) is developed for modeling this coupling process by explicitly introducing fracture networks embedded into porous media. Both fractures and rock matrix are discretized as connected pipe networks by a self-developed mesh generational tool in the discontinuum based method. A local thermal non-equilibrium (LTNE) model is introduced to separate the fluid and solid temperatures. Two energy balance equations are incorporated and connected by the heat transfer term. The proposed method is verified by comparing with the analytical solution and performing convergence tests. A case study is carried out by introducing randomly distributed fractures into a three dimensional rock mass. Sensitivity analyses are conducted to investigate the influence of the solid-fluid interface heat transfer coefficient, pressure differential and fracture aperture on temperature distribution in a highly fractured porous medium.

1. Introduction

Hot dry rocks (HDR) generally buried within 3–10 km depth contain enormous heat resources [14]. An enhanced geothermal system (EGS) is formed due to the extremely low permeability of HDR during geothermal development [39,40,12]. The ‘hydraulic stimulation’ method is commonly used to create man-made fractures to connect with natural fractures, generating fracture networks which allow heat transmission and fluid circulating in an artificial heat reservoir and finally facilitates the production of thermal energy [29]. Since the first attempt to make the full-scale EGS taking place at Fenton Hill, the EGS concept has been utilized in many field applications, including Soultz project in France [17,16], Habanero project in central Australia [37], Rosemanowes project in UK [18], Schönebeck project in Germany [46], etc.

The heat development in EGS is a complex process involving with hot water seepage, thermal transmission, chemical reaction and even mechanical effects [25,10,41,5]. Properties in each physical field are influenced by others. The optimized scheme for enhancing heat extraction can never be obtained without understanding the multiphysical coupling mechanism underground. On the other hand, the complex fracture network as a remarkable feature in geothermal reservoirs further obstacles estimating the performance of heat production. The distribution of fractures has great influence on flow patterns resulting in unpredictable thermal evolution process. Fracture networks maintain or even improve injection efficiency, and at the same time easily lead to the phenomenon of thermal breakthrough. The concept of fracture connectivity as an important property of a fracture network is still undefined, even though much work has been done [22,4,1]. Flow mechanism and heat transfer are affected by fracture geometries and surface properties (e.g. fracture roughness, tortuosity) [42,21].

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Channeling effect, for instance, normally caused by the unevenly distribution of the fracture aperture [13], adds the difficulty in revealing the hydro-thermal coupling process. Numerous studies have been carried out to solve the above issues in geothermal development by providing analytical and semi-analytical solutions. However, their applications are limited due to oversimplified model configurations and assumptions.

Numerical methods are comparatively more flexible and convenient, and thus are commonly implemented into simulating the multiphysical coupling process in fractured porous media. Continuum based methods are possible ways to model fluid flow and heat transmission in discrete fractures which are implicitly homogenized within porous media. Jiang et al. [14,15] used a single-porosity model by regarding a porous geothermal reservoir as an equivalent porous medium with a single porosity. The dual-porosity model is another equivalent way to simulate flow in both matrix and fractures [34], followed by the multiple interacting continua (MINC) model proposed for fluid and heat flow [24] and reactive geothermal transport [38] in fractured porous media. Kalinina et al. [19] used the multi-porosity model to simulate the effects of heterogeneity on geothermal development. Stochastic continuum model [32] is also an effective method to predict global hydraulic and thermal response. These equivalent scenarios, nevertheless, eliminate the detailed information of fractures such as geometry and connectivity, and thus cannot reflect the influence of fracture networks on pressure and temperature distribution.

Some discrete models are based on the concept of discrete fracture networks (DFNs) where large numbers of fractures with a wide range of sizes are explicitly embedded into continuous media. Two-dimensional discrete models are commonly employed in the simulation of the thermal development in fractured hot dry rocks. Sun et al. [29] used the commercial software COMSOL Multiphysics to simulate the thermal-hydro-mechanical coupling process in heat extraction by introducing randomly distributed one-dimensional fractures. Fracture surface roughness was considered in the DFNs model and its influence on heat transfer was analyzed at a macroscopic level [21]. Three dimensional simulation is more reliable than these two dimensional models mentioned above, even though the computational cost is comparatively higher. Kolditz [17,16] employed a discrete finite element approach to describe the flow and transport in three dimensional fractured geothermal system. Equivalent pipe network (EPN) was proposed to analyze the heat distribution with steady state flow by simplifying 3D fracture networks as one-dimensional pipes connected with each other [37]. The contribution of matrix is not considered in the EPN framework. A discrete mathematical model established by [47] integrated thermal-hydro-mechanical effects, and was used in a practical case of deep HDR geothermal extraction system. Still only two parallel fractures with large sizes are embedded in a simplified cube ‘reservoir’. Several poro-elastic based or chemical introduced mathematical models [9,10,26] were proposed to simulate the evolution of fracture apertures during the heat extraction process. However, just one fracture was considered by connecting a production well and an injection well.

Moreover, most of these three dimensional approaches neglect the effect of heat transfer between solid and fluid phases and use only one energy balance equation based on the local thermal equilibrium (LTE) theory. Identical temperature in porous material is assumed to indicate the instantaneous local temperature equilibrium. This assumption simplifies the numerical formulation and improves computational efficiency. However, studies show that the local thermal equilibrium is not established if rapid heating or cooling happens in underground formation with numerous fractures and fissures [11,7]. Furthermore, local temperatures between matrix and fracture are not identical if the fracture spacing is more than two-three meters [30]. The effect of heat transfer in fractured porous media is addressed by introducing a local thermal non-equilibrium (LTNE) method [14,7]. Two energy balance equations are employed to describe the temperature distribution of solid and fluid phases, respectively. Both heat convection and conduction terms are considered for the fluid phase, while only the heat conduction term for the solid phase. The heat exchange process is enabled by a heat transfer term and controlled by a heat transfer coefficient [8].

The present study aims to simulate the three dimensional hydro-thermal coupling process in highly fractured geothermal reservoir based on the LTNE model. A unified pipe-network method (UPM) is employed for its convenience to deal with both matrix and fractures in the framework of discrete fracture networks. The discretized fracture pipes are explicitly embedded into matrix pipes. Fluid temperature and solid temperature are assigned to each node and solved according to two energy balance equations. The influence of seepage field on temperature distribution is established by including the convective effects existing in the fluid energy equation. Flow pattern changes with fluid properties which are affected by the fluid temperature. This T-H coupled model is verified against an analytical solution. Convergence tests are carried out for the LTNE based mathematical model by considering one rectangular fracture embedded in a porous domain. The effects of fracture aperture, heat transfer coefficient and production pressure differential on the heat extraction process in highly fractured formation are analyzed.

2. Mathematical model

In the current mathematical model, we assume that only single phase (fluid) exists in the hot fractured reservoir. The fluid density does not change with temperature. The fluid flow in both rock matrix and fractures obeys the Darcy’s law. Mechanical and chemical effects are not considered in following simulations. The thermal dispersion, and radiation effects are also ignored.

Based on the above assumptions, governing equations involved in this T-H coupled process are introduced. The fluid flow in both fractures and matrix can be described by a mass balance equation:

$$\frac{\partial}{\partial t}(\phi^{\tau}\rho_f) = \nabla\cdot(\rho_f\cdot\vec{u}) + \rho_f q, \tag{1}$$

where ρ_f is the fluid density; q is the source term; τ is a sign for each medium in the model ($\tau = m$ for matrix, $\tau = f$ for fracture), thus ϕ^m is the matrix porosity, and ϕ^f is the fracture porosity; $\vec{u}$ is the flow velocity vector. Based on Darcy’s law, this term can be written as:

$$\vec{u} = -\frac{\boldsymbol{K}^{\tau}}{\mu}(\nabla P - \rho_f\vec{g}), \tag{2}$$

where μ is the fluid viscosity; P represents the pressure in the system; $\vec{g}$ is the gravitational acceleration; $\boldsymbol{K}^{\tau}$ is the intrinsic permeability tensor for matrix and fracture. The cubic law is employed in this study for simulating fluid flow in fractures, and thus the intrinsic permeability for fractures can be estimated as $k^f = a^2/12$. a is the fracture aperture [45].

Two sets of energy balance equations are introduced for rock matrix based on the LTNE model. Both heat convection and conduction are considered in the fluid phase, and the energy conservation is written as:

$$\phi^m\rho_f c_f\frac{\partial T_f}{\partial t} + \rho_f c_f\nabla\cdot(\vec{u}\cdot T_f) = \nabla\cdot(\phi^m\lambda_f\cdot\nabla T_f) + h_{\text{int}}(T_s - T_f), \tag{3}$$

where T_f is the fluid temperature; T_s is the solid temperature; c_f is the heat capacity of the fluid; λ_f is the thermal conductivity of the fluid; and h_{int} is the solid-fluid interface heat transfer coefficient. It should be noted that h_{int} is a constant and not influenced by fluid velocity and fracture aperture in the current assumption [11,14,30]. In the solid phase, only heat conduction is considered in the energy conservation:

$$(1-\phi^m)\rho_s c_s\frac{\partial T_s}{\partial t} = \nabla\cdot((1-\phi^m)\lambda_s\cdot\nabla T_s) + h_{\text{int}}(T_f - T_s), \tag{4}$$

where ρ_s is the rock density; c_s and λ_s are the heat capacity and thermal conductivity of the rock, respectively.

The heat conduction term is not taken into account within fractures,