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Heat extraction mechanism in a geothermal reservoir with rough-walled fracture networks

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ABSTRACT

This study aims at understanding the mechanism of heat extraction from a geothermal reservoir characterized by rough-walled fracture networks. A unified pipe-network method (UPM) which simplifies both fractures and the rock matrix as pipes is developed considering the local thermal non-equilibrium (LTNE) theory, and it is verified against an analytical solution. Three-dimensional simulations of macroscopic fluid flow and heat transfer in a fractured geothermal reservoir are conducted to take account of fracture roughness. The channeling effect and the heterogeneous distribution of fluid temperature in a core-scale model with a rough-walled fracture surface are simulated. An equivalent heat transfer coefficient (EHTC) is obtained from numerical experiments with respect to the flow rate, mechanical aperture and the equivalent hydraulic aperture. A representative element volume is then used to investigate the flow and heat transfer process in a geothermal reservoir with rough-walled fracture networks by applying the obtained EHTC. Results demonstrate that it is essential to use the proposed EHTC since the constant heat transfer coefficient (HTC) recommended in previous studies underestimates the final outlet fluid temperature in cases with rough-walled fractures.

1. Introduction

Geothermal energy is a renewable and clean energy that is mainly stored in the enhanced geothermal system (EGS) with complex fracture networks embedded in low permeable rock matrix [1,2]. It is important to evaluate the thermal production efficiency and potential of a geothermal reservoir [3,4]. Previous experiments have been performed to reveal multiphysical-interaction mechanisms in the process of heat extraction [5–7]. Still, numerical modelling is an effective tool in estimating heat recovery in geothermal reservoirs [8–11], and a local thermal equilibrium (LTE) theory is assumed in the classical heat transfer of fluid-saturated models [12,13]. The fluid and its surrounding matrix are considered as a single continuum, and the heat reaches the local equilibrium instantaneously. The LTE model improves the computational efficiency with an identical temperature shared by both fluid and matrix requiring to be calculated. Nevertheless, studies indicate that this model is not applicable if rapid heating or cooling process exists in the formation with multiple fractures [14,15]. Especially, the fluid temperature in fractures and the solid temperature along fracture walls cannot be locally identical if the fracture spacing is more than two to three meters [3]. Therefore, a local thermal non-equilibrium (LTNE) model [1,16–18] is introduced in the simulation of geothermal development by incorporating a heat transfer term controlled by the fluid-solid temperature difference, contact area at the interface and the heat transfer coefficient (HTC) [4,19–21]. The HTC determines the intensity of the heat transfer between the fluid and solid phases and thus is regarded as a critical parameter in the estimation of thermal production.

Numerous work including experimental and theoretical studies has been carried out to investigate the heat transfer coefficient. Based on the convectional core-scale triaxial test platform with a cylindrical rock specimen installed, a series of flow-through experiments were performed by injecting the cool fluid into a man-made fracture of the rock specimen which was continuously heated [22,23]. The influence of different fracture apertures and various flow velocities on the heat transfer effect was analyzed. Ogino et al. [24] determined an average heat transfer coefficient by using a physical model where water was injected into the two-dimensional circular fracture plane. Large scale tests were performed in Lu and Xiang [25] to investigate the effect of fluid flow on the temperature distribution considering several pre-set

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apertures in the granite. The most recent work carried out by Bai et al. [26] focused on characterizing the overall HTC. Flow and heat transfer tests were performed using a newly developed multi-field triaxial test system to precisely estimate thermal properties of rock specimens under different confining pressure, confining temperature and fluid flow rate. Analytical models were also proposed on the establishment of experimental findings. A thermal boundary layer model was suggested by Chapman [27] to calculate the average HTC for the laminar fluid flow through a flat plate maintaining a constant temperature. However, it was demonstrated that this model overestimated the value of the HTC according to the study of Zhao [4]. In Zhao's work, a power correlation was found to determine the HTC by combining previous experimental results [23] and an analytical solution for a rectangular model embedded with a single straight fissure. Explicit results of the overall HTC based on a realistic half-disk model were provided in recent studies [26,28,29]. The analytical model [26] verified by the experimental results indicated that HTC was positively correlated with the fluid flow rate, while the coefficient decreased with the growth of the fracture aperture. Different from the above models in the steady-state condition, a transient solution was proposed to describe the local heat transfer process through a dynamic heat transfer coefficient [19]. This dynamic result was extended to simulate the heat transfer in a reservoir scale.

Most of the previous studies mentioned above were carried out on the basis of a smooth-walled fracture model with a constant fracture aperture. However, man-made or natural fractures in EGS are typically coarse and irregular [21]. The existence of rough-walled fractures, on one hand, greatly influences fluid flow patterns by generating the channeling effect [30,31]. Channels, formed by the random distribution of fracture apertures along the fracture surface, are characterized with the tortuous property and have variable aperture along their length [32]. In the spatially heterogeneous aperture fields, the fluid flow in these passages tends to be channelized along several preferential paths. The "channeling effect" is thus defined as a phenomenon of preferential paths filling with an increasing portion of the fluid flow [31]. On the other hand, the impact of fracture roughness on the heat-transfer mechanism between fluid and fracture walls is also demonstrated in literatures. According to the experimental and theoretical studies by He et al. [33], the heterogeneous distribution of the local HTC was mainly controlled by the degree of fracture roughness. Recent experiments [34] compared the convection heat transfer characteristics between distilled water flow in a man-made smooth-walled fracture and a rough-walled fracture, and concluded that the heat transfer effect was intensified with the increase of the fracture roughness. Nevertheless, these qualitative findings cannot be directly employed to the simulation of geothermal development. And few studies have been done to find the quantitative relationship between the HTC and the fracture roughness.

It is also a great challenge to simulate the heat transfer in a three-dimensional model embedded with rough-walled fracture planes, even though numerous discrete fracture network (DFN) based models were proposed to simulate engineering problems such as CO_2 sequestration, heat mining and oil&gas development by assuming that all fractures were smooth [35–42]. Grids with extremely small sizes were assumed to be applicable to model the aperture distribution along fracture surfaces, aiming at precisely describing the surface properties. The fluid flow channeling effect was discussed based on the small sized grid in literature [43–45]. However, these accurate simulations are only applicable to a core-scale model, since the high computational cost exists if extremely large numbers of elements are generated on fracture planes in a 3D macroscopic model to reflect the fracture surface roughness. On the other hand, the random distribution of apertures for each fracture in fracture networks with complex geometries is another difficult task to be solved.

An equivalent parameter analysis strategy can be the effective solution for the aforementioned difficulties. In this study, the fluid flow and heat transfer in both core-scale and representative elementary volume (REV)-scale models are simulated using a unified pipe-network method (UPM). This numerical method incorporating the LTNE theory is verified against analytical solutions with different mesh strategies along fracture surfaces. In the core-scale model with a rough-walled fracture surface, the channeling effect and the heterogeneous distribution of fluid temperature are simulated. An equivalent heat transfer coefficient (EHTC) is quantitatively obtained from numerical experiments with respect to the flow rate, equivalent hydraulic aperture (EHA) and mechanical aperture. Instead of precisely describing the aperture information in each fracture node, equivalent parameters including the EHA and EHTC obtained are used to simulate macroscopic flow and heat transfer process in a 3D REV model embedded with rough-walled fractures. The influences of different mechanical apertures and fracture surface properties on the efficiency of heat transfer are investigated. The significance of considering EHTC in the modeling of geothermal development is also addressed by comparing with the situation using the constant HTC suggested by previous studies [1,3].

2. Mathematical model and numerical method

In this study, the single-phase fluid flow and heat transfer is assumed in both rock matrix and fractures. The pressure and flow rate distributions are evaluated with Darcy flow, and Cubic law is assumed to be valid in the local area of the fracture surface. The local thermal non-equilibrium (LTNE) theory is incorporated into a three-dimensional unified pipe-network method (UPM) with a single fracture or multiple fractures randomly generated in the domain. Chemical and mechanical effects are ignored in the current simulation.

2.1. Fluid flow and heat transfer

In the three-dimensional rock mass, both fractures and the matrix are considered for the fluid flow and heat transfer. The governing equations for pressure and temperature assuming LTNE in the steady state is:

$$\nabla\left(-\rho_f \frac{k^\tau}{\mu}\nabla P\right) = 0, \tag{1}$$

$$\rho_f c_f \nabla\cdot(\vec{u}\cdot T_f) = \nabla\cdot(\phi^\tau \lambda_f \cdot \nabla T_f) + h^\tau_{\text{int}}(T_s - T_f), \tag{2}$$

$$\nabla\cdot((1-\phi^m)\lambda_s\cdot\nabla T_s) + h^m_{\text{int}}(T_f - T_s) = 0, \tag{3}$$

where P is the fluid pressure; ρ_f is the fluid density; τ represents each medium in the model ($\tau = f$ for the fracture, $\tau = m$ for the matrix), and ϕ^f is the fracture porosity, while ϕ^m is the matrix porosity; $\vec{u}$ is the flow velocity which can be expressed as $\vec{u} = -(k^\tau/\mu)\nabla P$ based on Darcy's law; μ is the fluid viscosity; k^τ is the intrinsic permeability, and k^f equals to $e^2/12$ for fractures according to the Cubic law, e is the hydraulic aperture [46]; T_f and T_s represent the fluid temperature and the solid temperature, respectively; c_f is the fluid heat capacity; λ_f and λ_s represent the fluid thermal conductivity and the solid thermal conductivity, respectively; h^τ_{int} is the solid-fluid interface heat transfer coefficient; h^f_{int} is expressed as $2h/e$ for heat transfer along fractures [4], h is the fracture heat transfer coefficient; h^m_{int} is the solid-fluid interface heat transfer coefficient of the rock matrix. The term on the left side of Eq. (2)