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APPLICATION OF A DUAL-CONTINUUM MODEL FOR SIMULATION OF FLUID FLOW AND HEAT TRANSFER IN FRACTURED GEOTHERMAL RESERVOIRS

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ABSTRACT

This study aims to develop a dual-continuum model with the focus on a rigorous representation of discrete factures and their interaction with surrounding rock matrix, which therefore allows for a reliable prediction of impacts of fracture-matrix interaction on heat transfer in fractured geothermal formations. In this continuum model the fracture and matrix systems are treated as two separate overlapping continua, each of which has its own mass and energy balance equations. The balance equations for two continua are coupled through matrix-fracture heat transfer. An upscaling technique is used to transform discrete fracture characteristics to equivalent fracture continuum parameters, which involves direct mapping of discrete fractures onto continuum grid blocks by calculating grid-based effective permeability tensor. The model was calibrated against a fine-scale discrete-fracture model to further constrain fracture-matrix heat transfer coefficient, leading to an improved calculation of heat exchange between the fractures and matrix. We also applied this approach to simulate the thermal-hydrologic (TH) behaviors of fracture-stimulated geothermal reservoirs.

INTRODUCTION

Modeling of fluid flow and heat transfer in fractured rocks is of particular importance for energy recovery analysis of an engineered geothermal system (EGS), and therefore represents a critical component for EGS system design and performance evaluation.

As we know heat transfer through fractured rocks is controlled by the interplay between thermal convection in the fractures and conduction in the matrix. Within fractured porous media, fluid flow and thermal transport processes are typically simulated at two representative scales, namely, discrete fracture, and continuum scales. Theoretically, discrete fracture models, which explicitly account for individual fractures, should be able to capture the physical behaviors at various scales. However, practical application of these models at field scales is often computationally limited. For this reason the continuum modeling approaches are often used to simulate field-scale fluid flow and heat transfer processes in fractured geothermal reservoirs, which are based on either equivalent continuum model (ECM) (e. g. Wu, 1999), or dual continuum model (DCM) and its various extensions (e.g. Pruess and Narasimhan, 1985, Lichtner, 2000). The ECM model, using equivalent porous media with averaged rock properties to represent fractured systems, is simple but less accurate, especially when considering the problems with large permeability contrast between fracture and matrix (e. g. Wu, 1999). The DCM or multiple interacting continua (MINC) models (e.g. Pruess and Narasimhan, 1985), on the other hand, treat the fracture and matrix systems as two separate continua, in which flow and heat transfer are conceptually addressed in both matrix and fracture continua. Each continuum has a complete set of its own mass and energy balance equations. The balance equations for two continua require a coupling term to describe inter-continuum mass and heat transfer. This approach is useful and efficient particularly when a subsurface system (such as a heterogeneous reservoir) has too many fractures or too complex fracture networks to be explicitly represented.

As pointed out by previous studies (e.g, Lichtner, 2000), one of the largest challenges or uncertainties facing continuum-scale models is whether or not the so-called homogenized matrix-fracture properties are able to capture the main features of a fracture system, and hence effectively represent matrix-fraction interactions. In order to address this issue various forms of fracture continuum (FC) models and related upscaling techniques have been developed during the past decades (e.g. Teimoori et al., 2004; Botros et al., 2008; Reeves et al., 2008a, b). Among them is a conceptual framework for mapping fractures onto continuum systems, which was proposed by Botros et al. (2008) and Reeves et al. (2008a, b). This approach, in which the discrete fractures are directly mapped onto regular-spaced finite difference grids by calculation of effective permeability or transmissivity tensor on a grid basis, can largely preserve geometric characters of discrete fracture networks in a continuum model, thus leading to improved modeling of fluid dynamics, and heat and mass transfer in fractured reservoir systems.

In this study we developed a dual continuum model, in which a fracture continuum (FC) approach was employed to transform discrete fracture characteristics to equivalent fracture continuum parameters, allowing for a rigorous representation of discrete factures and their interaction with surrounding rock matrix. The model was verified and calibrated against a high-fidelity discrete fracture model to further constrain fracture-matrix heat transfer coefficients. We also applied this model to investigate the thermal behaviors of fractured geothermal reservoirs, and quantify the impact of hydraulic stimulation on heat production and recovery for an EGS system.

MODELING APPROACH

Dual Continuum Model Formulation for Flow and Heat Transfer in Fractured Media

In this study single-phase flow and heat transfer processes in fractured geothermal reservoirs are considered. It is assumed that the fracture networks are the major pathways for flow and convective heat transfer, and the solid rock matrix is treated as impermeable but heat conductive. The fracture and matrix systems are treated as two overlapping and interacting continua, as illustrated in Figure 1.

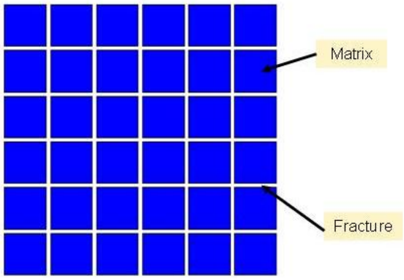


Figure 1 Conceptual schematic of dual-continuum (matrix-fracture) system.

The mathematical equations used to describe flow and transport processes in porous media are based on the principle of mass, momentum and energy conservation. Darcy's law is the well-known approximate momentum balance for fluid flow through a porous medium. Commonly used for hydraulic groundwater modeling, the mathematical formulation for mass transport of a single fluid phase in fracture media can be written in a general form as

$$\phi_f \frac{\partial \rho}{\partial \mathrm{t}} = -\nabla \cdot (\rho \mathbf{v}) + \Gamma \qquad (1)$$

Here t, ∇, and Γ respectively represent time, spatial derivative operator, and source/sink terms. φ_f is the porosity of the fracture, ρ is the fluid density, and the Darcy flux vector **v** is expressed as

$$\mathbf{v} = -\mathbf{K} \cdot \nabla \mathrm{h} \qquad (2)$$

in which h is piezometric head, and **K** denotes effective hydraulic conductivity tensor.

For a non-isothermal system the energy balance equations are expressed as

$$\frac{\partial}{\partial \mathrm{t}}[\phi_f \rho \mathrm{C_p} T_f + (1-\phi_f)\rho_s \mathrm{C_{ps}} T_f] + \nabla \cdot (\rho \mathrm{C_p} T_f \mathbf{v}) = \nabla \cdot (\mathbf{K}_\mathrm{T} \nabla \mathrm{T}_f) - \Gamma_{fm} + \mathrm{Q}_f \qquad (3)$$

for the fracture continuum, and

$$\frac{\partial}{\partial \mathrm{t}}[\phi_m \rho \mathrm{C_p} T_m + (1-\phi_m)\rho_s \mathrm{C_{ps}} T_m] = \nabla \cdot (\mathbf{K}_\mathrm{T} \nabla \mathrm{T_m}) + \Gamma_{fm} + \mathrm{Q}_m \qquad (4)$$

for the matrix continuum, in which the subscripts f and m denote fracture and matrix continuum, and T, $\mathrm{C_p}$, $\mathrm{C_{ps}}$, ρ_s, $\mathbf{K}_\mathrm{T}$ and Q denote temperature, specific heat of fluid and solid phases, solid phase density, thermal conductivity, and heat source term, respectively. The energy coupling term between fracture and matrix, Γ_fm, is defined as

$$\Gamma_{fm} = h_T A_{fm}\left(T_f - T_m\right) \qquad (6)$$

with $\mathrm{h_T}$ denoting heat transfer coefficient between fracture and matrix, and $\mathrm{A_{fm}}$ interfacial fracture-matrix specific area. Both $\mathrm{h_T}$ and $\mathrm{A_{fm}}$ are important parameters, influencing fracture-matrix interactions. While $\mathrm{A_{fm}}$ can be estimated based on geometric relations between fractures and matrix blocks $\mathrm{h_T}$ is typically computed by harmonic averaging of matrix/fracture thermal conductivities (e.g. Lichtner, 2000), in the form of

$$h_T = \frac{K_{Tf} K_{Tm}}{l_m K_{Tf} + l_f K_{Tm}} \qquad (7)$$

In numerical implementation $\mathrm{l_f}$ and $\mathrm{l_m}$ are taken as $\delta/2$ and L/2, with δ denoting fracture aperture width and L matrix block length.

Grid-based Effective Permeability Calculation

In this study the fracture continuum methodology proposed by Botros et al. (2008) and Reeves et al. (2008a, b) was employed to transform the discrete fracture network into hydraulic properties on a uniform Cartesian grid in a two-dimensional continuum model. The scheme of grid-based effective hydraulic conductivity calculation (Botros et al., 2008; Reeves et al., 2008a, b) is briefly summarized as follows, and also depicted in Figure 2. As described by Botros, et al. (2008) the volumetric Darcy flux $\mathrm{Q_{i,j}}$ between adjacent grid blocks i and j in two dimensional space is written as

$$Q_{i,j} = K_{i,j}(h_i - h_j) \qquad (8)$$

with (h_i – h_j) representing the head difference. The effective inter-grid hydraulic conductivity $K_{i,j}$ is approximated by adding up the contributions of all the fractures crossing the interface between grid cells i and j as (Botros et al., 2008)

$$K_{i,j} = \sum_{i,j}^{N} K_f^n \qquad (9)$$

K^n_f indicates the contribution of fracture n to inter-grid (i-j) conductivity with N denoting the number of fractures intersecting grid i-j interface, and is related to fracture transmissibility T^n_f by uniform grid spacing L as

$$K_f^n = {T_f^n}/{L} \qquad (10)$$

According to the cubic law the transmissibility for a fracture is defined as (Botros et al., 2008)

$$T_f^n = \frac{\rho g \delta^3}{12\mu} \qquad (11)$$

with δ as fracture aperture width, and g and μ indicating acceleration due to gravity and fluid viscosity, respectively.

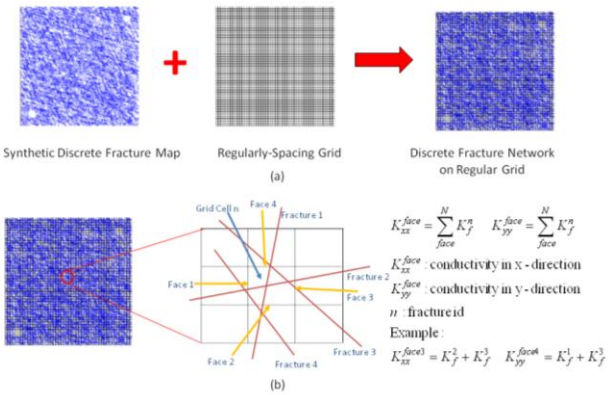


Figure 2 Conceptual schematic for grid-based effective hydraulic conductivity calculation (Botros et al., 2008; Reeves et al., 2008a, b) (a) The discrete fractures are mapped onto a Cartesian finite difference grid; (b) The effective hydraulic conductivity between grid cells in each principle direction is determined based on the intersections between fractures and grid cell faces in order to preserve the main fracture geometry/anisotropy.

Numerical Simulation Tool

The coupled fracture flow and heat transfer simulations were performed using the Nonisothermal Unsaturated-Saturated Flow and Transport code, NUFT (Nitao 1998; Hao et al. 2012). The NUFT code, which is based on Darcy’s flow approximation, represents a current state-of-the-art in modeling multiphase, multi-component heat and mass flow and reactive transport in unsaturated and saturated porous media. An integrated finite difference method is used for numerical discretization. Several mathematical models are implemented in order to address various flow and reactive transport processes in porous media. The NUFT code is a highly flexible computer software package capable of running on PCs, workstations, and major parallel processing platforms. Some of its application areas include: geothermal exploitation, nuclear waste disposal, CO_2 sequestration, groundwater remediation, and subsurface hydrocarbon production (e.g. Buscheck et al., 2003; Carroll et al., 2009; Glassley et al., 2003; Johnson et al., 2004).

Model Verification

In this verification test we applied the dual continuum model to simulate flow and heat transfer in a two-dimensional 100 × 100 m^2 domain with inter-connected fracture network, as shown in Figure 3. The initial reservoir temperature was 200 ^oC, and the cold fluid was injected at a temperature of 60 ^oC. The pressure difference between injection and production wells was maintained at 5 bars. The fracture aperture width is assumed to be uniform across the fracture network as 500 μm. The heat capacities of liquid and rock phases are 4174 and 860 kJ/kg/K, and their thermal conductivities are 0.6 and 2.0 W/m/K, respectively. The liquid viscosity is 0.0003 kg/m/s. The matrix porosity is assumed as 0.2. In order to assess the effects of fracture-matrix interaction on heat transfer we increased heat transfer coefficient at the matrix-fracture interface by up to 5 times larger than the value, h_T calculated from equation (7).

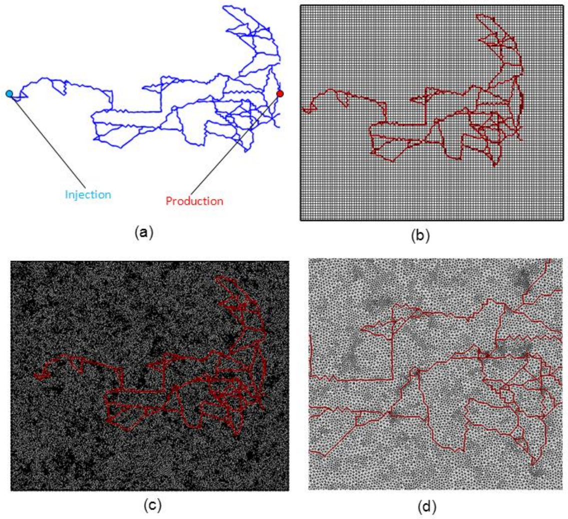


Figure 3 (a) The discrete fracture network; (b) The finite difference mesh for dual continuum model (DCM); (c) The finite element mesh for discrete fracture model (DFM); (d) Zoom-in, finite element mesh.

The same problem was solved by a fine scale finite-element based discrete fracture model. This discrete fracture model, which is capable of explicitly handling individual fractures and their surround matrix rocks, and as well as very complex geological features and geometries, has been validated in a separate study. In order to reduce numerical discretization errors, and in particular resolve the thermal boundary layer near each discrete fracture a fine grid resolution was employed as seen in Figure 3(c-d), thus providing a rigorous representation of fracture-matrix interaction for this test.

The history of temperature and heat recovery rate at the production well simulated by the dual continuum model (DCM) is compared with that obtained from the discrete fracture model (DFM) in Figure 4. The use of a larger fracture-matrix heat transfer coefficient leads to a better agreement between DCM and DFM solutions, reflecting potential scale-dependence of effective heat transfer coefficients. The reasonably good agreements for temperature spatial distribution are also observed in Figure 5.

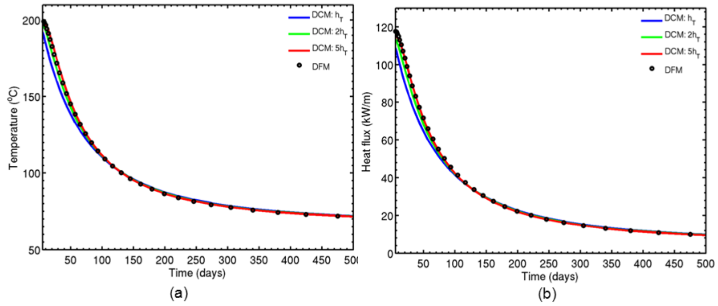


Figure 4 (a) The temperature history; (b) The heat recovery rate at the production well.

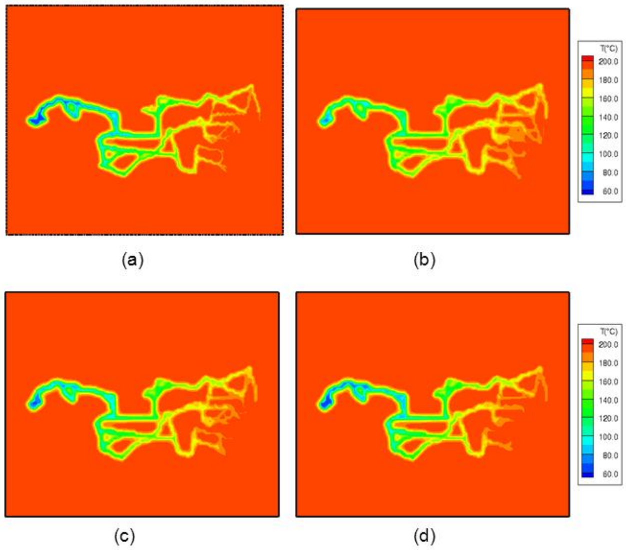


Figure 5 Snapshots of temperature at 17 days after injection simulated by (a) discrete fracture model (DFM), and dual continuum model (DCM) with (b) h_T; (c) 2 × hT; (d) 5 × h_T.

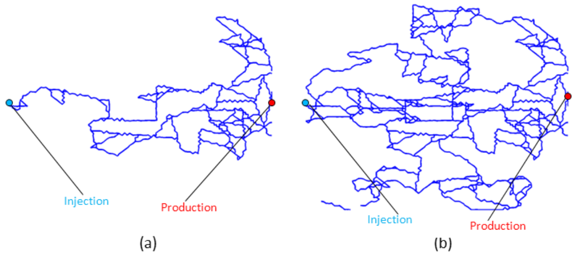
RESULTS AND DISCUSSION

Hydraulic stimulation, which is able to either create new factures (hydro-fracturing) or enhance fracture aperture (hydro-shearing), tends to form high permeable pathways for fluid flow and heat transfer, and thus enhance heat extraction/production for an enhanced geothermal system (EGS) (MIT, 2006). The stimulation techniques are generally divided into two major categories, hydro-fracturing and hydro-shearing, depending primarily on the pumping fluid pressure. As the fluid pressure exceeds the minimum principle stress in the rock formation hydro-fracturing or cracking occurs, which results in new fracture initiation and propagation. In hydro-shearing processes the fluid pressure is lower than that needed for tensile fracturing, but higher enough to induce shear movement on existing fractures.

In this study we used the dual continuum model to explore effects of fracture stimulation on flow and heat transfer processes and energy recovery for an EGS system. Two numerical examples are presented in this section, which are associated with hydro-fracturing and hydro-shearing processes, respectively. The discrete fracture networks used in the following simulations were obtained from separate geomechanical studies of hydraulic stimulation, which are detailed in Fu et al. (2011, 2012).

Effects of Hydro-fracturing on Heat Transfer in Geothermal Reservoirs

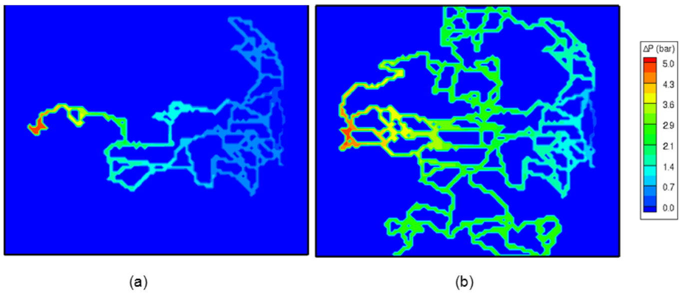
Figure 6 shows the formation of new fractures within an existing fracture network as a result of hydro-fracturing processes. The post-stimulation fracture network was obtained from separate hydro-geomechanical simulations (Fu et al., 2011, 2012).



(a) (b)

Figure 6 Discrete fracture networks (a) before stimulation; and (b) after stimulation.

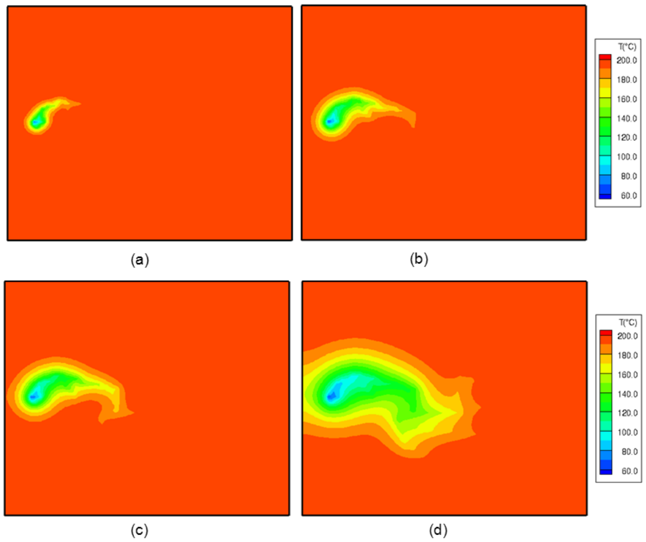
The heat transfers behaviors before and after fracture stimulation were modeled for a two-dimensional conceptual geothermal reservoir system, covering a 100 × 100 m^2 area with inter-connected fracture network. The model parameters are the same as those used for the model verification tests except that the fracture aperture width is assumed as 100 µm for this test case. Figure 7 displays steady-state pressure distribution within the pre-existing and stimulated fracture networks.



(a) (b)

Figure 7. Steady-state fluid pressure distributions for the cases of (a) without stimulation, and (b) with stimulation.

Figure 8 and 9 compare temporal and spatial thermal evolution profiles for the cases of without and with hydraulic stimulation, respectively. The thermal fronts for both of cases appear to move towards the production well, following the fractured pathways. Because of the presence of more inter-connected fractures heat transfer processes become more intensified in the stimulated fracture system, leading to thermal breakthrough within a 3-year time frame.



(a) (b)

(c) (d)

Figure 8 Spatial and temporal development of temperature distributions for the case of without stimulation at (a) 0.2 year, (b) 0.6 year, (c) 1 year, and (d) 3 years after the injection started.

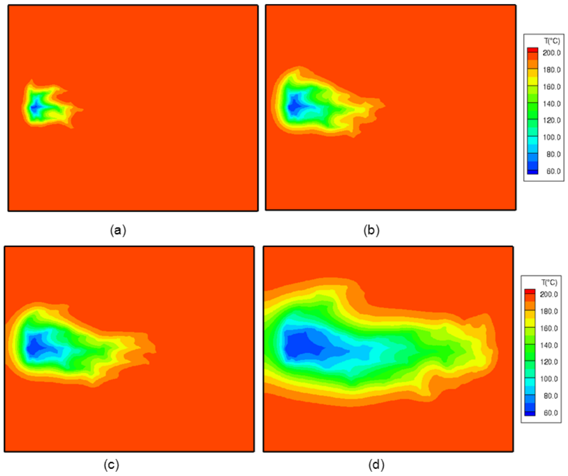


Figure 9 Spatial and temporal development of temperature distributions for the case of with stimulation at (a) 0.2 year, (b) 0.6 year, (c) 1 year, and (d) 3 years after the injection started.

Effects of Hydro-shearing on Heat Transfer in Geothermal Reservoirs

The hydro-shearing occurs when fluid pumping pressures are maintained at a level high enough to cause shear slip, but less than those required for hydro-fracturing conditions. Although there is no new fracture created during this process the system's permeability is enhanced through fracture aperture dilation.

For this case a two-dimensional simulation domain, representing a 250m-wide and 330m-long reservoir (Figure 10), is selected to study the effects of hydro-shearing on heat transfer processes. The discrete fracture network map with spatial variation of fracture aperture width (Figure 10) was obtained from the hydro-shearing simulation study conducted by Fu et al. (2012). According to geomechanical simulations hydro-shearing induced by fluid over-pressuring occurred through the pre-existing fracture network system, and considerably increased fracture aperture, and thus permeability in the near-well regions.

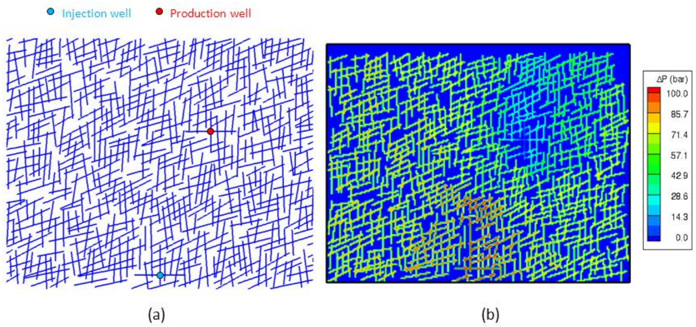


Figure 10 (a) Discrete fracture network used to assess the impact of hydro-shearing on heat transfer behaviors and energy recovery of an EGS system; (b) Quasi-steady state pressure distribution within the fracture network

During a 5-year period of fluid injection the pressure difference between injection and production wells were maintained at 100 bars. The quasi-steady state pressure distribution within the fracture network zones calculated by the continuum model is shown in Figure 10b. The comparison of spatial and temporal development of temperature distribution induced by cold fluid injection between the cases of without and with stimulation is made in Figure 11. At the early stage of injection (Figure 11a) very similar temperature distribution patterns near the injection well are identified for both of cases because as predicted by the hydraulic stimulation model most of fracture aperture enhancement occurred around the production well. A closed inspection of Figure 11b for the intermediate transient stage reveals that the thermal plume tended to move more sharply towards the production well with stimulation. The temperature evolution and energy extraction rates at the production well are compared between the cases of without and with stimulation in Figure 12. It is observed that the stimulation is able to help achieve up to ~20% increase in energy recovery before thermal drawdown.

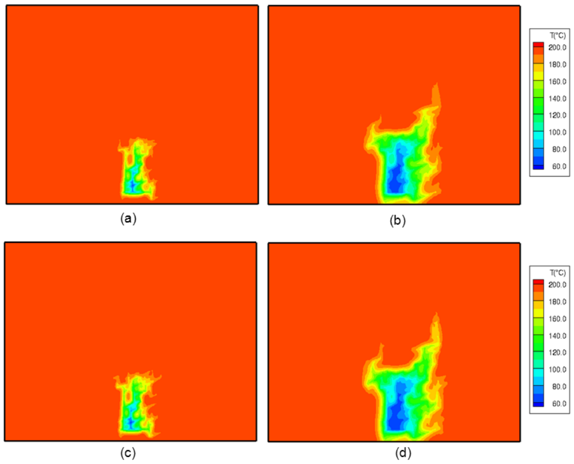


Figure 11 Spatial and temporal development of temperature distributions for the cases of without stimulation at (a) 0.5, (b) 2 years after injection; and with stimulation at (c) 0.5, (d) 2 years after injection.

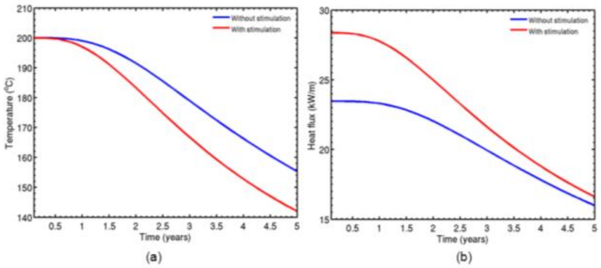


Figure 12 (a) The temperature history; (b) The heat recovery rate at the production well.

SUMMARY

In this study we have developed a dual continuum modeling approach to simulate fluid flow and heat transfer processes in fracture-stimulated geothermal reservoirs, in particular assessing and evaluating efficiency of heat transfer and energy recovery from an EGS system. The fracture continuum (FC) method implemented in this work enables accurate and efficient description of discrete fracture network systems. The model was verified and calibrated against solutions from a corresponding high-fidelity discrete fracture model. Moreover as demonstrated by the preliminary thermal modeling results this model can effectively account for coupled flow and heat transfer in both fractures and their surrounding matrix blocks with a dual continuum representation, which is essential for field-scale heat transfer analysis for an EGS system.

Additionally we used the dual continuum model to simulate the thermal-hydrologic (TH) behaviors of geothermal reservoirs in response to two common hydraulic stimulation scenarios, hydro-fracturing and hydro-shearing. The simulation results confirm that the heat transfer/production efficiency of an EGS can be greatly improved by the employment of either stimulation strategy.

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