Modeling investigation of the impacts of dead-end fracture on heat transfer of water flowing through rough fractured rocks

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Abstract. A clear understanding of the convective heat transfer characteristics of fluid in threedimensional (3D) rock fractures affected by dead-end fractures is important in evaluating heat recovery in fractured geothermal reservoirs. Two 3D cubic fractured rock models with and without rough dead-end fractures are built to conduct flow and heat transfer simulations by solving hydrothermal coupling equations. The rough fractures are upscaled from lab-measured small-scale rock fractures. Injection velocities of 0.002 m/s and 0.02 m/s were imposed to examine how dead-end fractures affect the heat transfer processes within hot fractured rocks. Several characteristic parameters, including outlet water temperature, total heat extraction, and overall permeability, are presented to quantitatively describe the effects of dead-end fractures. Results show that dead-end fractures retard fluid flow through the fractured model and significantly decrease the overall permeability. A low-temperature zone grows rapidly under the effect of dead-end fractures, and the outlet water temperature is lower in this case than in the model without dead-end fractures. Moreover, the total heat extraction is higher in the model without dead-end fractures than in the model with dead-end fractures. This result is mainly ascribed to the former model’s large overall permeability. Results reveal that dead-end fractures cannot be ignored in the evaluation of flow and heat transfer in the modeling of heat extraction from subsurface fractured geothermal reservoirs.

1. Introduction
Geothermal systems are usually established in the fracture formation of structures, and they provide the main fluid flow and determine reservoir permeability. Thus, understanding the heat transfer behavior within the subsurface fracture networks is crucial for optimizing heat extraction and improving the heat recovery factor of geothermal reservoirs [1,2].

Subsurface fracture networks are generally complicated, and they include normally distributed natural fractures and intersecting dead-end fractures. Numerous simulation studies deeply analyzed the effects of the characteristics of fracture network geometries on fluid flow and heat transfer [3–7]. The commonly used method is to regard a fracture as a planar object splitting the material in two parts with displacement discontinuity [2]. In addition, dead-end fractures are assumed to exert no effect on fluid flow and are thus always ignored during subsurface fluid flow modeling. These assumptions result in the underestimation of fluid flow behavior and miscalculation of heat transfer through complex fracture intersections. Such drawback is due to the main fractures and dead-end fractures being intrinsically heterogeneous [8]; moreover, complex fracture geometries, including variable void spaces and contacts, complicate flow characteristics and significantly limit the evaluation of heat transfer without the consideration of dead-end fractures. Previous studies by Zou et al. [9] and Zou et al. [10] indicated that three-dimensional (3D) dead-end fractures significantly affect solute transport and cause the retardation of transport in fractures. However, to date, only a few studies have explored the effects
of dead-end fractures on heat transport. Therefore, evaluating the heat transfer process of water flowing through rough 3D fractures intersecting with dead-end fractures is urgently needed to understand the heat transfer within subsurface fracture networks.

Motivated by this purpose, this work investigates the heat transfer process through 3D fractured rock masses with and without dead-end fractures and conducts hydrothermal coupling simulations. The 3D rough fractures are up-scaled from lab-measured small-scale rock fractures. Two different injection velocities are adopted to examine the heat transfer process with increasing flow velocities. The modeling results facilitate the understanding of heat transfer in subsurface fractured geothermal reservoirs.

2 Modeling description

2.1 Mathematical models

The following assumptions were made to simplify the flow and heat transport through rock fractures: 1) the rock matrix was assumed to be more impermeable than the rough fractures, 2) the local thermal equilibrium (LTE) assumption was adopted to describe the continuity of temperature from the fracture surface to the fluid at local points, (3) the boiling effects of the water were neglected during heat transport, and (4) the inertial forces in the fluid were negligibly small relative to the viscous and pressure forces. On the basis of these assumptions, the mass conservation equation and Stokes equation were solved to simulate the flow through rough rock fractures [11]; they are respectively written as

$$\nabla \cdot (\mathbf{u}) = 0 \quad (1)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} = -\nabla P + \mu \nabla^2 \mathbf{u} \quad (2)$$

where $\mathbf{u}$ is the velocity vector; $\mu$ and $\rho$ are the viscosity and density of the fluid, respectively; and $P$ is the reduced pressure defined by $P = p - \rho g \zeta$, where $p$ is the pressure and $\zeta$ is the coordinate pointing toward the direction of the gravitational acceleration.

Heat transfer in rocks is mainly governed by conduction, and the energy conservation equation of rocks is expressed as

$$\frac{\partial}{\partial t} (\rho_f c_v T) = \nabla \cdot (K \nabla T) \quad (3)$$

where $\rho_f$ is the solid density; $c_v$ is the solid specific heat capacity; and $T$ and $K$ are the absolute temperature (K) and heat conduction coefficient of the rock, respectively. Heat transfer in fracture fluid is predominantly governed by convection and conduction, and the corresponding energy conservation equation is expressed as

$$\rho_f C_p f \frac{\partial T}{\partial t} + \rho_f C_p f \mathbf{u} \cdot \nabla T_f + \nabla \cdot (-k_f \nabla T_f) = -\mathbf{n} \cdot K \nabla T_f \quad (4)$$

where $\rho_f$ is the fluid density; $C_p f$ is the specific heat capacity of the fluid at constant pressure; $T_f$ and $K_f$ are the fluid temperatures and heat conduction coefficients of the fluid, respectively; and $\mathbf{n}$ is the normal vector of the fracture surface. The hydraulic and thermal properties of water vary with temperature and are calculated using the internal COMSOL temperature-dependent water properties [12]. For the granite rock, the density is 2,643 kg/m³, the specific heat capacity is 1,000 J/kg·K, and the heat conductivity is about 2.4 W/m·K.

2.2 Computational geometries

Cubic fractured granite rock with a side length of 2m was built (Figure 1). Two orthogonal 3D rough fractures, both obtained from the upscaling of 3D scanned small-scale rock fractures, were embedded in the middle of the model (Figure 1-a) to highlight the influence of complicated fracture geometries on heat transfer. Another cubic fracture rock model without dead-end fractures was built to highlight the
impact of dead-end fractures on heat transfer (Figure 1-b). Injection flow rates of 0.002 and 0.2 m/s were imposed on the inlet to investigate the effect of increasing flow rates on heat transfer behavior.

The initial temperature over the whole computational domain was set as a constant temperature of 423.15 K. The temperatures of the top, bottom, and back faces of the computational domain were also 423.15 K, and the rock mass had no flow (Figure 2). Two fractures were initially saturated with water, and two fracture surfaces and the lateral boundaries of the fractures were specified as impervious and nonslip boundaries, respectively. The constant injection temperature of 313.15 K and flow rate at the left of the main horizontal fracture were fixed. The rock walls at the inlet and outlet and the front boundaries of the model were treated as adiabatic. The meshing of the intersecting fractures is illustrated in Figure 3. The meshes around the rock fractures were refined to improve the accuracy of the simulation. A total of 6 and 13 million tetrahedral meshes were set for the models with and without dead-end fractures, respectively. A transient solver was used for a total heat transfer period of 10 days with a time step of 0.3 h.

Figure 1 Schematic of 3D computational models with and without dead-end fractures
2.3 Flow and heat characteristic parameters
Several characteristic parameters, including overall permeability, outlet water temperature, and total heat production, were defined to characterize the heat transfer performance of water flowing through rock fractures.

2.3.1 Overall permeability
The fluid flow through the main rough fractures with or without dead-end fractures was assumed to obey the linear Darcy flow. The overall permeability can be calculated as

$$k = \frac{(\frac{Q\mu}{w\nabla P})^2}{\sqrt{12}}$$

where $Q$ is the volumetric flow rate, $\nabla P$ is the hydraulic pressure gradient along the flow direction, $\mu$ is the dynamic viscosity of the fluid, and $w$ is the width of the fracture.
2.3.2 Outlet water temperature
The average outlet temperature at time $t$ was calculated with the following equation:

$$T_{\text{out}}(t) = \frac{\int_{A_{\text{out}}} T_f(x,y,z,t)u(x,y,z) \rho_f(x,y,z,T_f) c_{p,f}(x,y,z,T_f) \, dA}{\int_{A_{\text{out}}} u(x,y,z) \rho_f(x,y,z,T_f) c_{p,f}(x,y,z,T_f) \, dA}$$  \hspace{1cm} (6)

where $A_{\text{out}}$ is the total area of the water outlet. $T_f(x,y,z,t)$ is the water temperature at the location $(x,y,z)$ at time $t$. $\rho_f$ and $c_{p,f}$ respectively represent the density and specific heat capacity of the water that changes with the temperature.

2.3.3 Total heat production
The heat ($Q$) absorbed by water in the whole fracture pathway is equal to the heat transfer convection between the water and the inner surface of the fracture; hence,

$$Q(t) = H_{\text{out}} M - H_{\text{in}} M$$  \hspace{1cm} (7)

where $M$ (kg/s) is the mass flow rate; $H_{\text{in}}$ and $H_{\text{out}}$ are the fluid enthalpy at the fracture inlet and outlet, respectively; and $H = T_f(x,y,z,t) C_{p,f}(x,y,z,T_f)$ . Furthermore, the cumulative heat production denotes the total heat production during the working periods and is expressed as

$$Q_{\text{total}} = \int_{0}^{T} Q(t) \, dt$$  \hspace{1cm} (8)

3 Results and discussion

3.1 Flow behavior characteristics
Figure 4 shows the norm of the flow velocity magnitude field, $U = \sqrt{u_x^2 + u_y^2 + u_z^2}$, in sectional views of the $x$-, $y$-, and $z$- directions in model $a$ (without dead-end fractures) and model $b$ (with dead-end fractures) under the injection velocity of 0.002 m/s. The flow velocity is distributed nonuniformly in the main horizontal fracture in the two models due to the existing heterogeneous void spaces. The velocity approaches zero along the upper and lower fracture walls due to the no-slip effects and then reaches its maximum value in the midplane. The flow velocity is lower in the dead-end fracture (blue color) than in the horizontal fracture and remains the same. The dead-end fracture has a limited impact on the flow velocity distribution in the horizontal fractures. The maximum flow velocity in model $a$, 0.0018 m/s, is larger than that in model $b$, 0.0014 m/s, thereby significantly affecting the temperature distribution in the two cases, as discussed later.
Figure 4. Flow velocity distributions in two models without dead-end fractures (a) and with dead-end fractures (b) at injection velocity of 0.002 m/s. The color scale is the same for the two models.

The overall permeability $k$ calculated under different injection velocities for the two models are plotted in Figure 5. The permeability $k$ of model $a$ is two orders of magnitude larger than that of model $b$, and this result is mainly ascribed to the significant retardation of the fluid flow through the main horizontal fracture intersected by the dead-end fracture. Thus, the presence of dead-end fissure fracture can weaken the overall permeability of the fractured rock.
**Figure 5** Comparison of overall permeabilities calculated by two different injection velocities in two models

### 4.2 Temperature distribution

The evolution of the temperature distributions in the two models with dead-end fractures (a) and without dead-end fractures (b) under different injection velocities (0.002 and 0.02 m/s) is shown in Figure 6. The results reveal that with increasing running time, a low-temperature zone (LTZ) gradually forms around the fractures due to the stored heat in the rock extracted from the flowing cold fluid. The LTZ in model a is larger than that in model b because of the heat extracted through the dead-end fracture. The increase of velocity from 0.002 m/s to 0.02 m/s affects the LTZ more significantly in model a than in model b. After a running time of about 8.64E5 s (10 days), the LTZ range of model a is significantly larger than that of model b. This result implies that most of model a is cooled by the injected water. In addition, the outlet water temperature $T_{out}$ changes with time in the two models under different injection velocities (Figure 7). The temperature $T_{out}$ gradually decreases with the running time and finally tends to stabilize. Increasing injection velocity results in a rapid decrease in temperature, which then reaches stabilization. Generally, after a running time of about 8.64E5 s (10 days), the outlet water temperature in model b is lower than that in model a mainly due to the larger flow velocity in the former (Figure 4).
4.3 Evolution of cumulative heat production

Total heat extraction Q changes with time in the two models (a) with dead-end fractures and (b) without dead-end fractures under different injection velocities are shown in Figure 8. Generally, the Q values in the two models increase nonlinearly with time, and their increase tendency are almost the same. The total heat extraction Q in the model without dead-end fractures is two orders of magnitudes greater than that in the model with dead-end fractures. With an increase in injection rates, the total heat extraction Q increases to 110% for model a and 124% for model b. Equations (7) and (8) show that the total heat extraction over a period of extraction time is mainly determined by flow rates and the temperature difference $\Delta T$ between the outlet and the inlet. Under a constant injection flow velocity, $\Delta T$ for models a and b are almost equal (Figure 7); thus, the large flow rate due to the large overall permeability in model b results in heavy heat production Q. In addition, if a constant injection flow rate is applied at the inlet, the large overall permeability causes low flow velocity and further results in a large $\Delta T$ between the outlet and the inlet of the model. The resulting total heat production is also relatively large. Thus, the development of the permeability of fractured rock mass helps improve the total heat production.

**Figure 7** Outlet water temperature $T_{out}$ change with time in the two models under different injection velocities
4. Conclusion
Flow and heat transfer simulations through two different 3D cubic fractured rock models with and without rough dead-end fractures are conducted by solving the hydrothermal coupling equations. The goal is to investigate the impact of dead-end fractures on flow and heat transfer behaviors, which are often ignored in the modeling of subsurface fluid flow. Two different injection velocities are considered to examine the heat transfer process with increasing flow velocities. The main results are described as follows:

1) The flow velocity is lower in the dead-end fracture than in the main fracture. The dead-end
fracture has limited impact on flow velocity distribution, but it significantly reduces the overall permeability in the fractured rock due to the immobile zone of water flow forming within the dead-end fracture. This zone retards the water flow through the main fracture.

2) The dead-end fracture causes the complexity of the temperature distribution in the fracture model, and this complexity is most notable at a high injection velocity. Although the dead-end fracture has little impact on fluid flow, an LTZ forms within this fracture through heat extraction, and the range of the LTZ expands with increases in injection velocity.

3) The outlet water temperature decreases nonlinearly with the extraction time and finally tends to approach stabilization. The total heat extraction in the model without dead-end fractures is two orders of magnitudes greater than that of the model with dead-end fractures mainly because of the overall permeability of the former. Dead-end fractures cannot be ignored in the evaluation of heat transfer in the modeling of the heat extraction process in complicated fracture networks.

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References
[1] Xu R, Zhang L, Zhang F, Jiang P. A review on heat transfer and energy conversion in the enhanced geothermal systems with water/CO2 as working fluid. Int J Energy Res 2015;39:1722–41. https://doi.org/10.1002/er.3352.
[2] Lepillier B, Yoshioka K, Parisio F, Bakker R, Bruhn D. Variational Phase-field modeling of hydraulic fracture interaction with natural fractures and application to Enhanced Geothermal Systems. J Geophys Res Solid Earth 2020:e2020JB019856. https://doi.org/10.1029/2020JB019856.
[3] Ma Y, Zhang Y, Hu Z, Yu Z, Zhou L, Huang Y. Numerical investigation of heat transfer performance of water flowing through a reservoir with two intersecting fractures. Renew Energy 2020;153:93–107. https://doi.org/10.1016/j.renene.2020.01.141.
[4] Zhang W, Qu Z, Guo T, Wang Z. Study of the enhanced geothermal system (EGS) heat mining from variably fractured hot dry rock under thermal stress. Renew Energy 2019;143:855–71. https://doi.org/10.1016/j.renene.2019.05.054.
[5] Shi Y, Song X, Li J, Wang G, Zheng R, YuLong F. Numerical investigation on heat extraction performance of a multilateral-well enhanced geothermal system with a discrete fracture network. Fuel 2019;244:207–26. https://doi.org/10.1016/j.fuel.2019.01.164.
[6] Qu Z, Zhang W, Guo T. Influence of different fracture morphology on heat mining performance of enhanced geothermal systems based on COMSOL. Int J Hydrogen Energy 2017;42:18263–78. https://doi.org/10.1016/j.ijhydene.2017.04.168.
[7] Fu P, Hao Y, Walsh SDC, Carrigan CR. Thermal Drawdown-Induced Flow Channeling in Fractured Geothermal Reservoirs. Rock Mech Rock Eng 2016;49:1001–24. https://doi.org/10.1007/s00603-015-0776-0.
[8] Pyrak-Nolte LJ, Nolte DD. Approaching a universal scaling relationship between fracture stiffness and fluid flow. Nat Commun 2016;7:10663. https://doi.org/10.1038/ncomms10663.
[9] Zou L, Cvetkovic V. Modeling of flow and mixing in 3D rough-walled rock fracture intersections. Adv Water Resour 2017. https://doi.org/10.1016/j.advwatres.2017.06.003.
[10] Zou L, Frampton A, Cvetkovic V. Impacts of dead-ends on flow and transport in fractured rocks. 2nd Int. Discret. Fract. Netw. Eng. Conf. DFNE 2018, Washington: American Rock Mechanics Association; 2018.
[11] Selvadurai APS, Couture CB, Rezaei Niya SM. Permeability of wormholes created by CO2-acidized water flow through stressed carbonate rocks. *Phys Fluids* 2017;29:096604. https://doi.org/10.1063/1.5002129.

[12] Freels JD, Bodey IT, Lowe KT, Arimilli R V. 2D Thermal Hydraulic Analysis and Benchmark in Support of HFIR LEU Conversion using COMSOL(ORNL/TM-2010/018). Oak Ridge National Laboratory (United States): 2010.