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Numerical Characterization of Heat Transfer Properties at Fracture Intersections with Dead-Ends

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INTRODUCTION

Understanding heat transport in fractured rock formations is essential for a wide range of geothermal applications. These include predicting production temperature and production life in enhanced geothermal systems (Bataillé et al., 2006; Daniilidis et al., 2021), optimizing storage and recovery of thermal energy in fractured media (Doonechaly et al., 2024; Gelet et al., 2013), and using heat as a tracer to infer hydraulic and thermal properties of fractured sites (De La Bernardie et al., 2018; Klepikova et al., 2016).

This study investigates the coupled thermal-hydraulic (TH) processes that govern heat transfer in such environments. Fluid flow predominantly occurs within the fracture network, enabling convective heat exchange between the fluid and the surrounding rock. Convective heat transfer between fractures and the rock matrix, along with advective transport driven by fluid movement, interacts with conductive heat transfer in the rock matrix driven by temperature gradients. Heat conduction is determined by the thermal conductivity of the rock matrix and the geometry of the fluid-rock interface.

The conditions of fluid flow are controlled by the hydraulic and structural characteristics of the fracture network, such as fracture length distribution, permeability, connectivity, and the type of fracture intersections (Davy et al., 2013). While the impact of intersections, particularly T-intersections and dead-end fractures, has been studied for solute transport (Yoon et al., 2023; Zou et al., 2018), their influence on heat transport remains less explored. Here, we consider a system consisting of two fractures: a production fracture extending between the inlet and outlet, parallel to the mean flow direction, and a dead-end fracture connected perpendicularly to the other one. We employ numerical simulations to assess the impact of the dead-end fracture on the thermal breakthrough curves and on the heat transfer between the injected fluid and the rock matrix, as a function of the Reynolds and thermal Péclet numbers.

1 METHODOLOGY

1.1 Numerical Simulations

The numerical model distinguishes two domains: a fluid domain representing the fractures and a solid domain representing the rock matrix. Flow and heat exchanges in the fluid domain are governed by the conservation equations for mass, momentum, and energy. The rock matrix is considered impermeable; therefore, the solid domain is subjected to heat conduction alone. At the interface between the two regions, continuity of the fluid and solid temperatures, $T_f = T_s$, and balance of the heat fluxes, $q_f = -q_s$, are enforced as boundary conditions The initial temperature, $T_{initial}$, is uniform throughout the domain, the inlet boundary conditions prescribe inlet velocity and inlet temperature, T_{inlet}. In this study, the inlet temperature is higher than the initial temperature. Zero gradient boundary conditions are applied at the surfaces of the solid region.

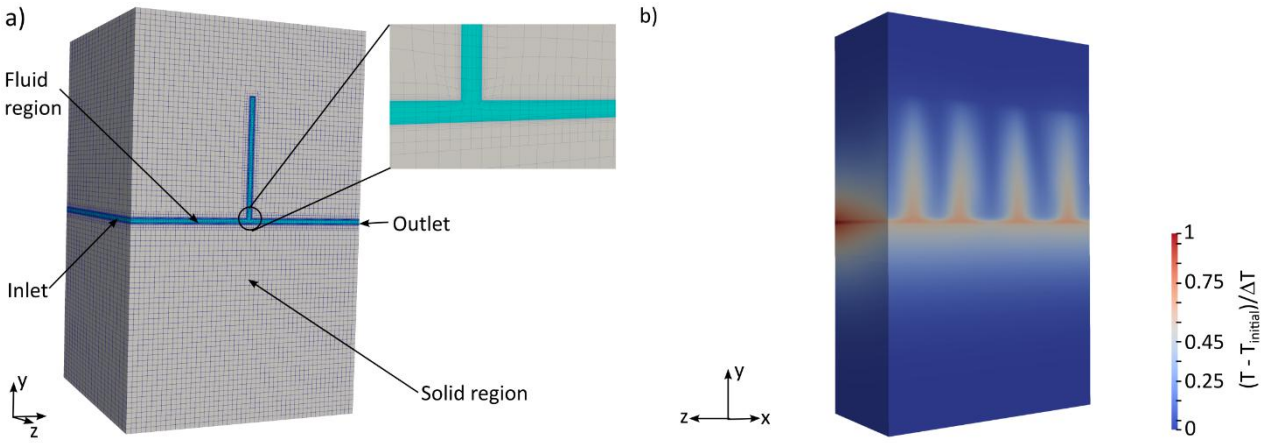


Figure 1. Discretization of the simulation domain showing the fluid region, solid region, and inlet and outlet surfaces (a), exemplary temperature distribution in the middle plane of the dead-end fracture (b).

The fluid properties, density, thermal conductivity, viscosity, and heat capacity, are temperature-dependent values. Gravity acts in the y-direction. The simulations rely on the "chtMultiRegionFoam" solver of the open-source computational fluid dynamics software OpenFOAM.

Figure 1a shows the simulation domain and its discretization. The main fracture, which connects the inlet and outlet surfaces, is positioned in the middle of the computational domain, so that its distances to the top and bottom boundary surfaces are equal. A temperature difference, and thus corresponding density difference, between the T-intersection and the end of the dead-end fracture above it, may induce buoyancy-driven natural or free convection within the dead-end fracture, as illustrated exemplarily in Figure 1b.

1.2 Test Cases

The influence of Reynolds and Péclet numbers on heat transport is investigated by varying the inlet velocity. The characteristics of each test case are summarized in Table 1. The simulations are performed for two different configurations: one for a fluid region that includes a dead-end fracture (Figure 1a) and one that excludes it. The inlet temperature, the thermal conductivity of the matrix, and the fracture aperture are constant and identical for all test cases. The Rayleigh number, estimated from the maximum possible temperature difference, consistently exceeds the critical Rayleigh number, suggesting the potential onset of natural convection.

Table 1. Properties of the different test cases.

Inlet velocity [m/s]	Reynolds number	Péclet number	Rayleigh number
0.001	2.0	2.5	$3.5 \cdot 10^7$
0.0034	6.8	8.6	$3.5 \cdot 10^7$
0.005	10	12.6	$3.5 \cdot 10^7$
0.01	20	25.2	$3.5 \cdot 10^7$

2 RESULTS

The results are presented in terms of the following normalized quantities: $T^*_{outlet} = (T_{outlet} - T_{initial})/\Delta T$, $q^* = q/(\dot{m} c_p \Delta T)$, and $t^* = (t/L) \cdot v_{inlet}$. The heat flux is defined with respect to the fluid region. A negative heat flux indicates a heat transfer from the fracture to the solid region. The simulation results are illustrated in Figure 2, i.e., the observed temperature at the outlet, the heat flux integrated over the whole interface area, and the heat flux integrated over the area of the dead-end fracture for all test cases.

As shown in Figure 2a, increasing the inlet velocity accelerates the temporal increase in the outlet temperature. For all Reynolds numbers, the outlet temperature is consistently higher in the configuration without the dead-end fracture (Figure 2b). This difference remains because free convection enhances the heat exchange between the main fracture and the dead-end fracture, therefore maintaining a larger mean

temperature in the dead-end fracture and thus resulting in more efficient heat transfer from the dead-end fracture to the surrounding matrix (Figure 2c). Hence, more heat is transferred from the injected water to the rock when a dead-end fracture is present.

At lower inlet velocities, heat transfer from the fluid to the matrix becomes more significant due to reduced advective transport in the main fracture connecting the inlet and outlet, and heat conduction in the solid regions determines the overall behavior, consistent with the low thermal Péclet number. For the same reason, a heat transfer from the matrix to the dead-end fracture is present at the initial time steps ($t^* < 4.1$ for $v_{inlet} = 0.001\,m/s$ and $t^* < 2$ for $v_{inlet} = 0.0034\,m/s$ and for $v_{inlet} = 0.005\,m/s$). Once the thermal front in the main fracture reaches the T-intersection, natural convection starts and reverses the direction of heat transfer between the matrix and the fluid in the dead-end fracture (Figure 2c). Independent of the inlet velocity, as the rock matrix warms, the temperature difference between the fluid and the matrix diminishes, which in turn weakens at later time steps the heat exchange between the two, and thus, the convective heat transfer within the dead-end fracture.

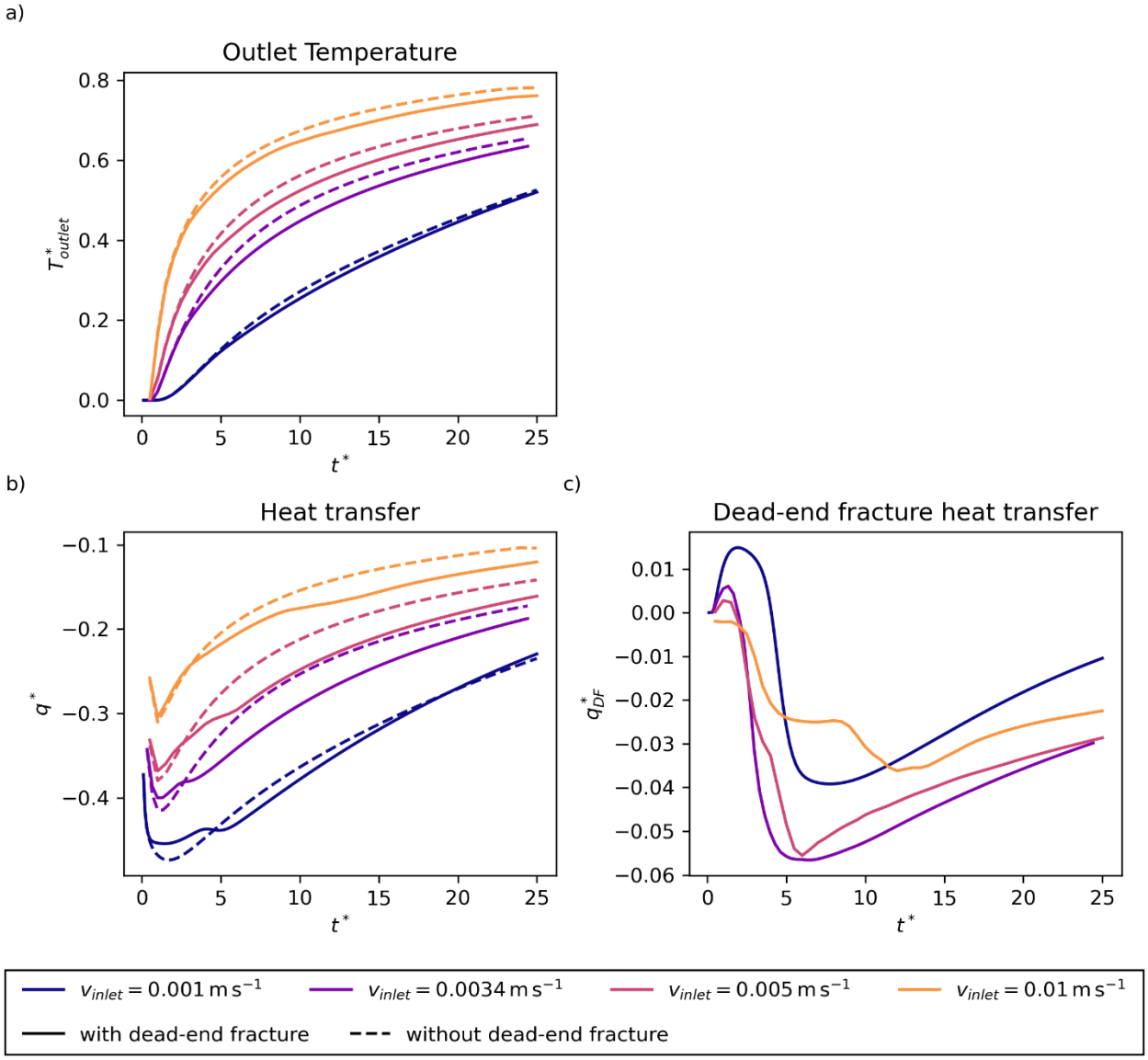


Figure 2. Evaluation of the simulation results of the different test cases (Table 1) from the temporal evolution of the outlet temperature (a), the surface heat transfer (b), and the heat transfer through the surface of the dead-end fracture (c).

3 CONCLUSIONS AND OUTLOOK

This study contributes to a better understanding of TH processes relevant to geothermal applications. The results highlight the interplay between advective, convective, and conductive heat transfer in fracture networks with T-intersections and dead-end fractures. By simulating fluid flow through configurations with and without a dead-end fracture, we demonstrate that the presence of dead-end fractures significantly impacts thermal breakthrough and heat exchange dynamics. Note that we have considered here a warmer injected fluid and a dead-end fracture oriented towards the top, but inverting the temperature difference and the direction of the dead-end fracture would provide the exact inverse quantitative results. Hence, the study applies both to configurations of heat tracing (as presented here) and geothermal operation.

Future work will extend this framework to study the influence of matrix thermal conductivity, fracture mean aperture and aperture heterogeneity, and inlet temperature difference. Integrating mechanical deformation coupled to fluid flow and heat transport, i.e., thermal-hydraulic-mechanical (THM) processes, can contribute to investigating the long-term performance of geothermal reservoirs. Ultimately, these insights aim to support the design and operation of enhanced geothermal systems.

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