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Sensitivity Analysis of Thermal Single-Well Injection-Withdrawal Tracer Tests for Evaluating Fracture-Matrix Heat Transfer Area

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As a means to enhance the amount of recoverable geothermal energy, development of enhanced geothermal systems (EGS) has been pursued. In order to improve the flow and heat transfer characteristics of the hot dry rock, stimulation treatments, which involve water injection under pressure, are commonly applied. The treatment increases the aperture and permeability of the pre-existing fracture network and creates additional fractures in the rock. While the increase of the permeability of the fractures is advantageous for the production of the thermal energy, rapid migration of injected waters through preferential paths with insufficient heat transfer from the rock may result in premature thermal breakthrough at production wells. Therefore, for successful operation of the EGS, it is important to assess the effect of stimulation treatments on both permeability of the fracture network and fracture-rock matrix interface area.

Single-well injection-withdrawal (SWIW) tests with temperature itself as a tracer can particularly be used to characterize available interface area for heat transfer between the reservoir rocks and the fractures or assess its change as a result of stimulation treatments. The thermal SWIW test entails injecting cold water into a well and, after quiescent or shut-in period, producing the water from the same well. In addition to the typically much shorter test duration of the SWIW test compared to interwell tests, the thermal SWIW test may have advantages for estimating heat transfer area because temperature returns at the well are directly dependent on the total available interface area for heat transfer between the reservoir rocks and the fractures. For this purpose, however, the sensitivity of thermal breakthrough during the recovery phase to the change in the fracture-matrix interface area is critical.

In this study sensitivity analysis is performed to determine the impact of the interface area and the effective aperture of the fracture as well as various operational conditions, including injection and/or extraction flow rates and the duration of quiescent time, on the thermal breakthrough. Thermal breakthrough during the recovery phase is examined by using an idealized model. For simplicity a vertically oriented homogeneous fracture is considered with the assumption of 1-D linear flow along the fracture.

While more rapid temperature increases were observed at the well during the recovery period as the fracture-matrix interface area increased, the temperature returns from the thermal SWIW test were insensitive to changes in the effective fracture aperture. This insensitivity of the temperature recovery profile to the effective aperture changes is desirable with respect to estimating the fracture-matrix interface area because this means the alteration of the hydrodynamic properties of the geothermal reservoir would not interfere in the interpretation of the SWIW test results for the estimation of the fracture-matrix interface area. The difference in the temperature transients during the recovery phase can solely be attributed to the increase of the fracture surface area as a result of the stimulation treatment.

The adjustment of the operational parameters induced notably different thermal breakthrough curves. As the injection and extraction flow rate decreased but with the same total amount of water injected, the integrated difference of two temperature return curves with different interface areas significantly increased. By slowly injecting water, the influence of heat transfer from the rock to the passing water flow was increased, and the temperature difference at the beginning of the recovery phase was magnified. The injection flow rate, however, affected spatial temperature profiles. As the flow rate was lower, the distance influenced by the cold water injection was reduced. That is, while a lower flow rate is advantageous to enhance the difference of temperature recovery profiles, it reduces the actual test region characterized by the SWIW test. The lower extraction flow rate helped to delay the returning time of the thermal front, therefore allowing temperature differences by the different fracture surface areas to be observed for a longer time.

On the other hand, when the injection time was prolonged with the proportional increase of the total amount of water injected, the temperature difference at the beginning of the recovery phase was reduced. However, owing to the longer injection time, thermal conduction in the wallrocks, induced by cold water injection into the fractures, was enhanced and the penetration depth of the cooling front was increased. As a result, the temperature differences persisted for a longer period. In the similar reason, no or a shorter quiescent time was favorable to increasing the integrated difference of thermal breakthroughs before and after stimulation treatments.