Thermal retardation in fractured media : theory and field evidence through heat and solute tracer test experiments

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The characterization of flow and transport in fractured media is particularly challenging because hydraulic conductivity and transport properties are often strongly dependent on the geometric structure of the fracture surfaces. Here, we derive analytical expressions for the retardation and decay of the thermal breakthrough peak amplitude for different fracture geometries et flow fields (Figure) that may be very useful to predict thermal transport from solute tracer tests or to characterize the fracture geometry from thermal tracer tests. We use those developed expressions to interpret the results of single well thermal tracer tests performed in a crystalline rock aquifer at the experimental site of Ploemeur (H+ observatory network).

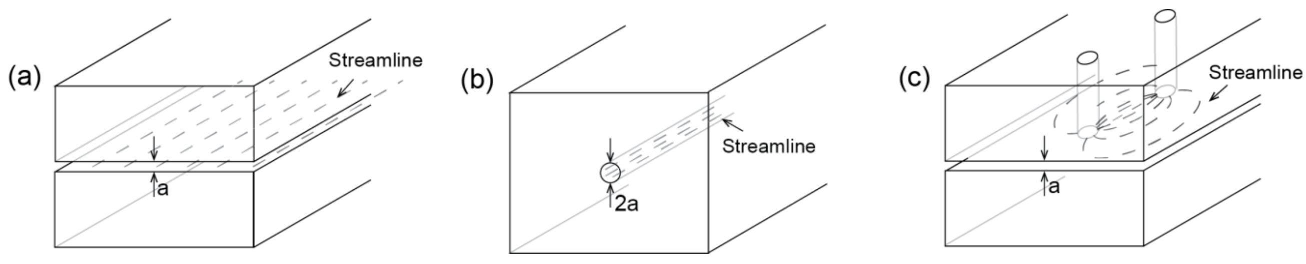

Figure : 3-D illustrations of the different fracture geometries with (a) a parallel plate fracture in linear flow field, (b) a channel fracture in a linear flow field and (c) a parallel plate fracture in a dipole flow field. a is the fracture aperture for the parallel plate fracture and the radius for the channel geometry.

The experimental setup is based on injecting a pulse of hot water in a fracture isolated by a double straddle packer in the borehole while pumping at the same flow rate (perfect dipole flow field) and monitoring the temperature in the same borehole above the straddle packer. After heat injection, ambient temperature water has been injected at same flow rate to remain in perfect dipole condition all along the tracer test. We implement a Fiber-Optic Distributed Temperature Sensing (FO-DTS) which allows the temperature monitoring with high spatial and temporal resolution (29 centimeters and 1 minute respectively).

FO-DTS was particularly useful to identify different inflows of variable temperatures which correspond to two flow paths connecting the injection to the withdrawal fracture. Only one of both flow paths contributes to thermal recovery. Expressions of the thermal retardation and amplitude were then used to interpret the thermal breakthrough curve, using a solute tracer test as a reference for the advection time. We demonstrate through those expressions that observed thermal amplitude and delay, which is shorter than expected, refer more to a channel fracture of large diameter than to a parallel plate fracture. It suggests that flow channeling strongly reduces thermal exchanges between the fractures and the matrix, which increases heat recovery. These findings, which bring new insights on the effect of flow channeling on heat transfer in fractured rocks, show how heat recovery in geothermal systems may be controlled by fracture geometry. This highlights the interest of thermal tracer tests as a complement to solute tracers tests to infer fracture aperture and geometry.