Modeling of heat transport through Fractures with emphasis to roughness and aperture variability

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- **Introduction :**

Fractured media are characterized by multi-scale heterogeneities implying high spatial variability of hydraulic properties. At the fracture network scale, spatial organization of fluxes is controlled by the fracture network geometry, itself characterized by fracture connectivity, fracture density, and the respective lengths and apertures of the fractures within the network. At the fracture scale, the variability of the fluxes is mainly controlled by fracture roughness and aperture variability. The multi-scale heterogeneities of fractured rocks imply complexities for prediction of solute and heat transport in space and time, and often lead to the so-called “anomalous transport” behavior. In homogeneous media, heat transport can be described using Fourier´s law opening the possibility to apply the advection-dispersion equation to predict transport behavior. However, in real fractured media a “non-Fourier transport” often dominates. The latter phenomenon, characterized by asymmetric breakthrough shape, early breakthrough and long tailing cannot be described by the classical advection-dispersion equation.

In the present study, we focus on heat transport within a single fracture and we explore the respective roles of fracture roughness and aperture variability. Fracture roughness has two main effects on heat transport, flow channeling and a spatial variation of heat exchange area between fluid and rock. Fracture aperture variability controls the variability of fracture flow, and thus induces spatial variation of heat transport in a fracture. Micro- to macro-scale fracture roughness measurements will be performed in the field and the laboratory using a terrestrial LIDAR, a X-Ray CT-Scanner Alpha, and a Microscope Keyence VHX 100. Thereafter the measurements will be used to better describe fracture geometry taking in account discontinuity type. To further improve the understanding of heat transfer between fracture and matrix, we will numerically model heat transport as function of fracture roughness and variable aperture using fracture roughness measurements from micro- to macro-scale natural fractures. Fracture roughness measurements will be analyzed by geostatistical and spectral methods in order to characterize fracture heterogeneities and to evaluate and simulate synthetic fracture geometries. Measured and calibrated synthetic fractures will be used to parameterize numerical heat transport models. We anticipate that these models will reproduce adequately anomalous (non-Fourier) transport behavior and will permit to better understand this behavior.

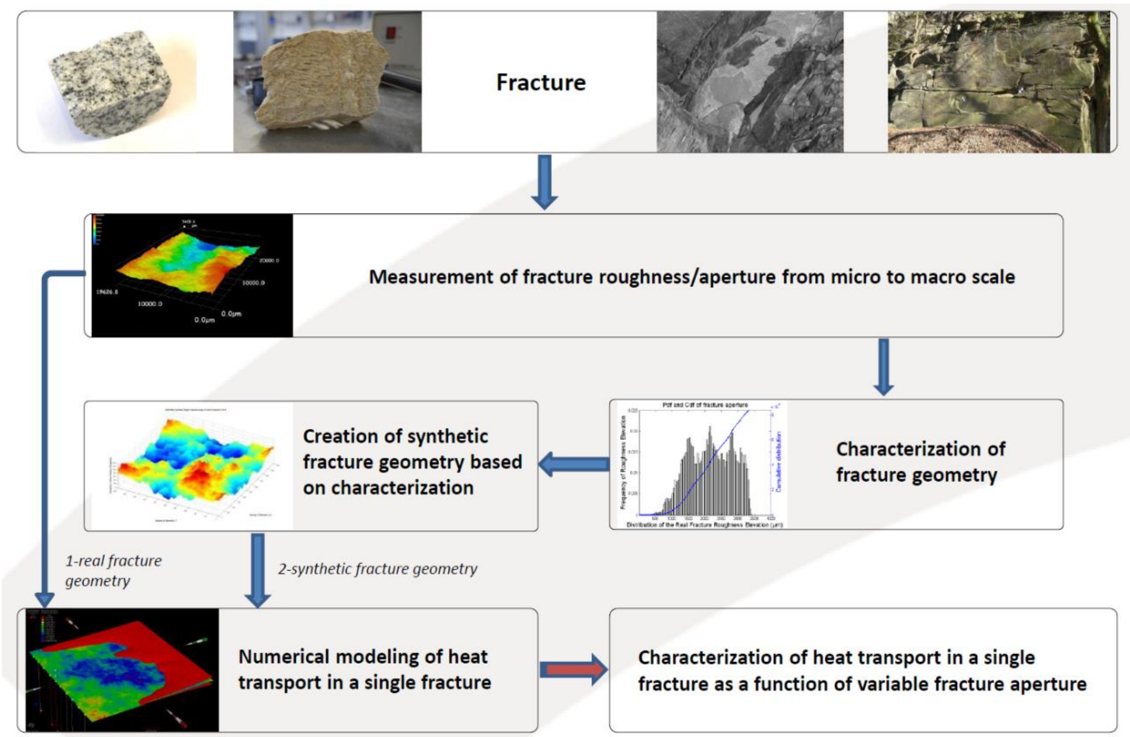

Fig.1: Schematic approach of the integration of complex fracture geometry in heat transport models

- **Why using variable fracture aperture in Heat Transport models?**

Many hydrogeological models are using the assumption of a plane fracture with a constant aperture to describe the transfer of flow, solute or heat transport in fractured media. In order to increase our understanding of heat transport in fractured media and to improve the efficiency of EGS system, the integration of complex fracture geometry based on real measurements into heat transport models is an innovative approach. Breakthrough curves during heat and solute transport models/experimentation in heterogeneous media often present a behavior called anomalous transport. In theory, the heat transport can be described using Fourier Law which implies the possibilities to use the advection-dispersion equation (ADE) to predict the behavior of heat transfer in time and space. In realistic fractured media or a single fracture with variable aperture, breakthrough curves often present a behavior called Non-Fourier Transport which is characterized by asymmetric breakthrough shape, early breakthrough and a long tailing. In this case, the classical advection-dispersion equation is not available to describe the transport processes.

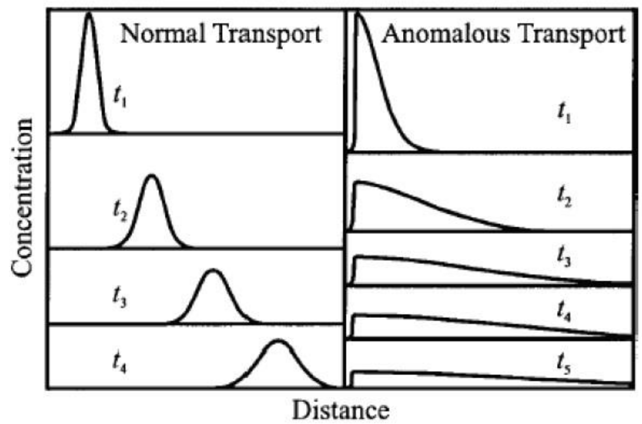

Fig.2: Normal Transport VS Anomalous Transport. Berkowitz and Scher, 2001

The conclusion of this research will be to clearly qualify and quantify the role of the fracture geometry on anomalous transport, then to propose viable methods to predict heat transport in single fracture by keeping a control on geometrical and hydrogeological parameters.

- **Measurement and characterization of Fracture surface**

To adequately describe the transport processes in rough fracture, an approach of fracture roughness through scales is required to explore the different possibilities induced by complex geometries. Using our facilities, measurement of fracture surface on 7 orders of magnitude on the fracture plane will be done. Concerning large scale measurement, a LIDAR Scanner Focus 3D X330 is used to realize measure on fresh fracture wall outcrops. After having collected samples on fracture outcrops, measurement at micro-scale are performed by using a Keyence VHZ-100UR microscope. A complementary method using a CT-Scanner should permit to realize directly micro-scale measurement of fracture aperture with the advantage of not being a destructive method towards the fracture sample.

In order to characterize fracture roughness, geostatistical and spectral methods were developed to extract representative parameter of the surface roughness. The spectral method consists of computing the power spectral density of the fracture topography which is assumed as a self-affine surface. In the case of statistical invariance of fracture topography, an exponent (the Hurst exponent) controlled by the vertical dilation of the self-affine distribution is extractable and can be considered as a great indicator of the fracture roughness. Two complementary geostatistical methods, auto-covariance function and semi-experimental variogram were also developed which provide great estimation of correlation length of fracture topography.

- **Synthetic Rough Fracture**

Several objectives lead to the creation of synthetic rough fracture. Induced by a time limitation concerning fracture measurements, the creation of equivalent synthetic fractures is a possibility to test a great amount of heat transport models in single rough fracture. By comparison with real fracture measurements, this development should permit to determine if a synthetic rough fracture can replace a real one. In case it does, it opens the opportunity to study the impact of different fracture geometry characteristics on heat transport. In order to create synthetic rough fracture, two main methods were developed voluntary using the same parameters that the ones extracted during roughness characterizations. The first method is the Sequential Gaussian simulation, based on kriging controlled by an empirical variogram and the definition of correlation length in two direction of space. The second method is based on the concept of anisotropic self-affine surface for which Hurst exponents controls the distribution in 2 direction of space.

- **Impact of fracture roughness surface on heat transport**

The impact of fracture roughness on hydrodynamic properties and solute transport in fracture has been extensively studied, when researches concerning heat transport in fractured media are rarest. Concerning the impact of complex fracture geometry on heat transport two mains assumption can be made, a developed fracture roughness increases the surface area of heat exchange at the fracture/matrix interface, on the other side fracture roughness will induce a higher channeling of the flow. By extension of former studies, the first approach will be to determine for various geometrical conditions which processes (variation of surface or variation of channeling) dominates the heat transfer from the fracture to the matrix.

The second and more challenging step is to define a clear method to predict the heat transport in heterogeneous media as a function of variable fracture geometry. By a differentiation of normal transport characterized by non-correlated velocities inside the media and anomalous transport for which velocities are correlated, some already developed methods and new ones will be used to relate the rock heterogeneities and the variabilities of velocities. The objective is to be able to fit breakthrough curves of anomalous heat transport, to find a relation with real fracture geometrical characteristic, and eventually being able to inverse this process.