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

Benoit Nigon [(1)], Andreas Englert [(2)], and Christophe Pascal [(2)]

(1) International Geothermal Center Bochum, Bochum, Germany
(2) Institute of Geology, Mineralogy and Geophysics, Ruhr-University, Bochum, Germany

Contact email: benoit.nigon@hs-bochum.de

ABSTRACT

In homogeneous media, heat transport can be described using Fourier´s law opening for 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 spatial variation of fluid/rock heat exchange area. Fracture aperture variability controls the variability of fracture flow and thus induces spatial variation of heat transport in a fracture. Macro-scale fracture roughness measurements have been made in the field using a terrestrial LiDAR. The measurements will be used to better describe fracture geometry taking into account discontinuity type. To further improve our understanding of heat transfer between fracture and matrix, we numerically will model heat transport as function of both fracture roughness and variable aperture using fracture roughness measurements from micro- to macro-scale natural fractures. Fracture roughness measurements will be analyzed by means of geostatistical and spectral methods in order to characterize fracture heterogeneity 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 result in valid simulation of anomalous (non-Fourier) transport and will permit to better understand this behavior.

Keywords: Fracture, Aperture, Heat transport

1. INTRODUCTION

Fractured media are characterized by multi-scale heterogeneities implying high spatial variability of hydraulic properties. At fracture network scale, spatial organization of fluxes is controlled by fracture network geometry, itself characterized by fracture connectivity, fracture density, and respective lengths and apertures of fractures within the network. At fracture scale, flux variability 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 lead often to the so-called "anomalous transport" behavior. Many geoscientific disciplines usually assume natural fracture as a single plane in order to simplify models. However, an approach taking fracture surface using real fracture measurement rendered easier by the development of recent and most powerful instrumentation, might improve fracture models and give insights on physical processes pertaining to rough fractures. This approach is expected to promote a better understanding of fracture heat transfer *(Anderson,2005; Geiger and Emmanuel,2010)***,** contaminant transport in fractures relevant for CO2 storage and nuclear waste (*Neretnieks,1980; Wang and Narasimhan ,1985)* exploitation of natural resources *(Gautam and Mohanty,2004),* rupture propagation *(Voisin et al,2002b),* seismic behavior *(Okubo and Aki,1987; Parsons, 2008),* and joint ornamentation *(Pollard and Aydin,1988).*

Recent studies have proposed fracture geometry characterization approaches to faults (fracture mode II or III) *(Kanninen and Popelar, 1985),* in order to describe fracture surface roughness at different length scales and its impact on rupture propagation. A similar approach for joints (fracture mode I) is seldom, because joint surface geometries dominated by plumoses remains more challenging to characterize. In addition, solute and heat transport studies at large scale are mainly based on fracture networks that involve planar fractures. This is typically the case for field tracer test experiments, when the laboratory scales are not providing the possibility to "explore" all the heterogeneities of the fractures and their respective impact. Solute transport studies including one single fracture scale were focused on fault. Considering that joints are the most common natural fractures (*Pollard and Aydin*, 1988), increasing the degree of knowledge on this aspect appears to be primordial.

To adequately describe heat transport processes in rough fractures, an approach dealing with fracture roughness at different scales is required to explore the different possibilities induced by complex geometries. A LiDAR Scanner Focus 3D X330 was used to measure fresh fracture faces. In order to characterize fracture roughness, geostatistical and self-affine method were developed to extract representative parameter about surface roughness. RMS correlation is considering fracture topography as a self-affine geometry, with a rescaling exponent (i.e. Hurst exponent) relevant for characterization of fracture roughness

(Schmittbull et al, 1995a; Candela et al, 2009). A complementary geostatistical method, the auto-covariance function was used to provide good estimations of fracture topography correlation length. The impact of fracture roughness on hydrodynamic properties and solute transport in fracture has been extensively studied, whereas studies on heat transport in complex fractured media are seldom. Concerning the impact of complex fracture geometry on heat transport two main assumptions can be made, (1) a pronounced fracture roughness increases surface area for heat exchange at the fracture/matrix interface; (2) fracture roughness induces higher channeling of the flow. Building on previous studies, the first approach will be to determine for various geometrical conditions what factors (variation of surface or variation of channeling) dominates the transfer of heat from the fracture to the rock matrix. The second and more challenging step is to develop a method to predict heat transport in heterogeneous media as a function of fracture geometry. Through differentiation of normal transport characterized by non-correlated velocities inside the media and anomalous transport for which velocities are correlated, methods both at hand and innovative will be used to relate fracture heterogeneity to variability of fluid velocities. The final goal is to explain breakthrough curves of anomalous heat transport, by finding relationship with real fracture geometries, and eventually, to conduct the inverse operation.

2. MATERIAL AND METHODS

Figure 1 summarizes the approach developed in this paper. The first step is to find quarries with freshly excavated joint surfaces and to scan them using LiDAR technologies. Characterization of joint surfaces is conducted numerically and relevant parameters (correlation length and Hurst exponent) are extracted. Real fracture geometries and synthetic fractures, but calibrated with our field data are finally integrated in heat transport numerical models.

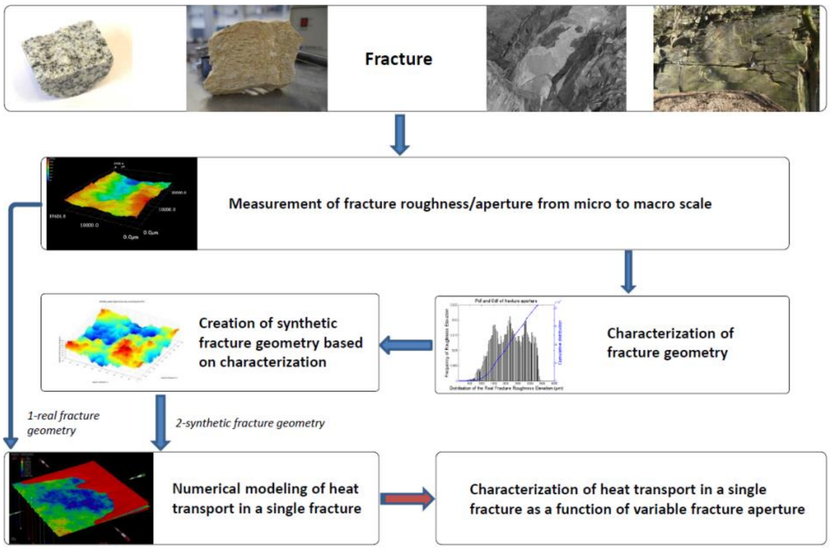

Figure 1: General approach developed in this paper

A Light Detection And Ranging Laser Scanner (LiDAR FARO® Focus3D X330) was used to build joint surface measurements of several square meters to tens of square meters. Accuracy of topographic models is ±2mm. LiDAR scanning was already applied to determine joint spacing in mines and outcrops (*Lato et al, 2010)*, to characterize joint roughness *(Lato et al, 2007)*, and to study fault roughness *(Renard et al, 2006, Candela et al, 2009).* In order to remove shadow area and to increase data acquisition by crossing measurement, several LiDAR scans were realized on the outcrop.

In this paper, two methods are presented to characterize joint surface, the RMS correlation method is based on the use of quadratic means as a function of varying window widths from series of profiles (2D surface). *Schmittbuhl et al, (1995a*) showed that a self-affine surface remains unchanged under scaling transformation

$$\delta x \rightarrow \lambda\, \delta x,\ \delta z \rightarrow \lambda^{H} \delta z \qquad [1]$$

of each 1D profile.
For a 2D surface, each parallel profile is divided into windows of width δx indexed by a varying origin point x_0 on the profile. RMS is computed for all δx, then plotted in log-log space for which the slope of the distribution follow positive power law controlled by Hurst exponent

$$\langle \sigma(\delta x) \rangle \propto \delta x^{H} \qquad [2]$$

The second method is a geostatistical description of the distribution of joint surface elevation, the autocovariance. The power of using an autocovariance function to characterize fracture surface consists in its ability to provide an estimation of correlation length on rough surface topography. Correlation length is a good indicator to characterize surface anisotropy. The autocovariance function is a statistic version of autocorrelation divided by the variance in order to normalize results in the range [- 1, 1]. It consists in studying the correlation along a profile by a4 shifted version of this same profile using:

$$Cov(x) = E [(X_i - \mu) . (X_{i+k} - \mu)], \qquad [3]$$

with E the expected error, μ mean value of x, X_i and X_{i+k} the elevation data of the original fracture profile x. Autocovariance is computed for each 1D profile, then averaged and normalized for the 2D surface (series of profiles). In case of repetitive structures on the surface (comparable to hills and valleys), this periodic behavior on a normalized plot of autocovariance will decreases from 1 to 0 from which is extractable the 2D surface correlation lag-length.

The effort to create synthetic fracture in this paper was motivated by the need of obtaining fracture apertures with controlled variable, in order to characterization methods before applying them to real fracture surface. However, a complementary approach developed in the course of the present study is to use synthetic fracture in heat transport models and to define which parameters, describing fracture geometry, are controlling heat transport. Finally one has to determine which one of these synthetic methods are the most reliable to reproduce realistic single fractures for a given type of rock and fracture (e.g. joint or fault). Two methods were used to reproduce synthetic fracture, the sequential Gaussian simulation (derived and adapted from the MATLAB code mgstat from SGEMS) which consists in defining a normal distribution on a regular grid, then defining a random path exploring all the grid nodes to finally proceed a kriging on the surrounding data by following an empirical variogram. The second method found and adapted from Candela et al, (2009), consists in generating Gaussian white noise on which a Fourier transformation is applied. The Fourier coefficients are multiplied by a power law (controlled by the Hurst exponent). Finally inverse Fourier transformation drive the results back to real.

In order to characterize anomalous transport induced by the flux variability in fracture, itself submitted to fracture roughness and aperture variability, we need to find the relationship between characterization parameters of fracture surface/aperture and anomalous behaviour of heat transport. To these aims, the LiDAR scan presented in *chapter 3* was input in COMSOL Multiphysics to compute preferential pathway/streamlines. The fracture flow model presented in this paper was calculated using a simple convection-diffusion equation approach, with the transmissivity controlled by the aperture from the LiDAR measurement.

3. PRELIMINARY RESULTS

A better understanding of the joint surface elevation distribution has been possible by combining Digital Elevation Models (DEM) from LiDAR scan measurements, with their characterization by autocovariance and RMS. The distribution of elevation in *figure 2* is showing clear trends that a Gaussian distribution is not sufficient to describe, and must be completed by using other roughness characterization parameters such Hurst exponent from RMS or correlation length from auto-variance (*fig.3*).

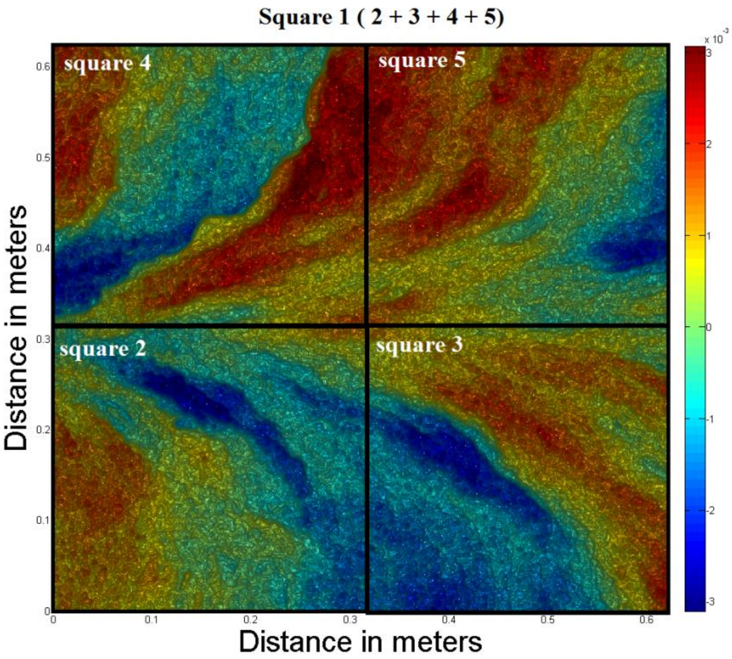

Figure 2: Digital elevation model of one joint surface derived from LiDAR scanning and, discretized in four parts for characterization. Color bar scale in meters

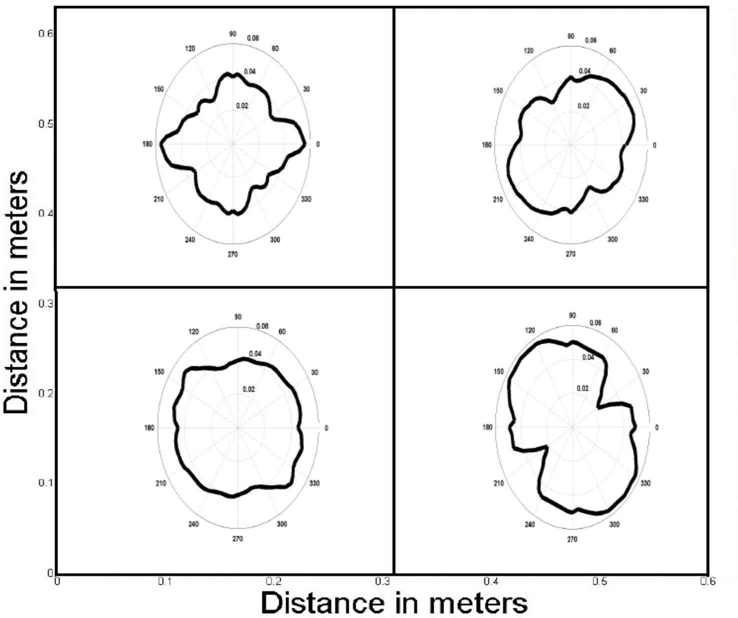

Figure 3: Multi-directional correlation length from autocovariance characterization, with their location given in figure1.

LiDAR scan measurements have confirmed their efficiency to obtain accurate DEM on rough fracture surfaces (*Candela et al, 2009; Schmittbull et al, 1995a)*. This method is suitable for joint surface geometry measurements, and makes the characterization of rough anisotropic surfaces by self-affine methods and geostatistical auto-covariance method possible. This work has shown that for a surface area of several square meters and a maximal difference between highest and lowest elevation of ~7 mm, these measurements highlights geometrical structures which are not perceptible to the bare eyes. The multi-directional correlation lengths in the *figure 3* are not all able to show a clear anisotropy on each discretized part of the DEM. On the other hand, for each multi-directional characterization, higher correlation lengths are consistent with the trends seen on the DEM (*fig.1*). The plumose is the main reason why it is difficult to distinguish a clear anisotropy for each discretized part of *figure 3.* Decreasing the typical sampling scale represents a solution to image anisotropy without influence of the curvature of the plumose. However, the objective is to define the full geometry of the joint surface in order to isolate its influence on heat transport. Plumose patterns remains extremely tedious to characterize compared to surfaces of mode 2 fractures, even if they produce unique geometries that are symmetrical to the joint propagation axis. This particular property of joint surface explains the necessity to discretize separately the two sides divided by the joint propagation axis (*fig.1*), in order to highlight the trends and correlations pertaining to the plumose structure (*fig.2*). In the case of a full joint surface characterization using the present methods (*square 1 on fig.2*), the results will show an isotropic geometry, wherever clear trends are present. As a consequence, in order to image the anisotropy of a full joint surface, a new method which unifies the complete surface will have to be developed.

Figure 4: Streamlines in stationary conditions showing heterogeneous advection using measured LiDAR joint geometry from *fig.1* rotated at 90°

Figure 4 depicts the impact of the joint geometry (geometry from *fig2* rotated of 90°) on the heterogeneous advection inside the fracture, as represented by streamlines, that follow the main flux pathway inside the fracture. The direction of streamlines provides an overview on how plumose influences the spreading of heat injection in such kind of media. The main geometrical structures on figure 1 are seen on the streamlines on *figure 2*, and highlight that the interplay between plumose geometry and directions of heat flow injection will lead to a high variability of preferential pathways. Considering one direction on *figure 4*, injection from the bottom may look as to reduce heat dispersion (geometry and flow pathways look mostly “convergent”), whereas injection at the top may induce higher dispersion (geometry flow pathways are looking mostly “divergent”). *Figure 4* suggests that heterogeneous fracture models are better suited for studying anomalous behavior of heat plumes, and shows nicely that correlation of velocities in space may be the principal cause of this phenomenon. By a differentiation of normal transport characterized by non-correlated velocities inside the media and anomalous transport for which velocities are correlated, continuous time random walk will be used to relate fracture heterogeneities and the variability in velocity. The objective is to be able to fit breakthrough curves of anomalous heat transport, to find a relation with fracture real geometrical characteristics, and eventually to be able to inverse this mutual relationship.

4. CONCLUSIONS AND OUTLOOK

LiDAR scan measurements have confirmed their efficiency to obtain accurate DEM on rough fracture surfaces. RMS and auto covariance methods show great efficiency to obtain complementary information for a discretized joint surface description after field study. However a new method in order to achieve the complete surface characterization will have to be developed. By quantifying surface anisotropy of joint surface and linking it to field studies, it will open the possibility to reach viable assumptions from characterization and to determine physical processes occurring on natural joint surfaces. DEM of joint surfaces acquired by means of LidAR scanning can be directly imported in numerical models of heat transport. This allows for bridging experimental laboratory studies (CT-scan fluid through experiment) and field studies (Heat push-pull test). The following step will be to relate characterization of joint surface heterogeneities and the variabilities of velocities using particle tracking methods, in order to describe anomalous heat transport.

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