Transverse mixing in 3D porous flows: experimental results & stochastic inference.

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Introduction

Mixing of dissolved chemical species in porous media plays a central role in many natural and industrial processes, such as contaminant transport and degradation in soils, oxygen and nitrates delivery in river beds, clogging in geothermal systems, CO2 sequestration.

In particular, incomplete mixing at the pore scale may strongly affect the spatio-temporal distribution of reaction rates in soils and rocks, questioning the validity of diffusion-reaction models at the Darcy scale. Recent theoretical [2] and numerical [3] studies of flow in idealized porous media have suggested that fluid mixing may be chaotic at pore scale, hence pointing to a whole new set of models for mixing and reaction in porous media.

In this talk, we present recent experimental evidence of chaotic mixing at the pore scale in 3D porous flows. Based on several measurements of the elongation of a material line, we propose a simple random walk model capable of capturing the main characteristic of chaotic advection in porous flows. We finally discuss the origin of this chaotic behavior and its most significant consequences for upscaling mixing and reactive transport in porous media.

Experimental measure of transverse mixing and spreading

We designed a novel experimental setup allowing high resolution pore scale imaging of the structure of a tracer plume in porous media columns consisting of glass bead packings. We conjointly used refractive index matching techniques and laser induced fluorescence to measure the mixing of a conservative tracer by the porous flow. We show that, moving away from the injection point, the plume cross-section quickly turns into complex, interlaced, filamentary structure whose length ℓ grows exponentially 1, reminiscent of chaotic mixing phenomena.

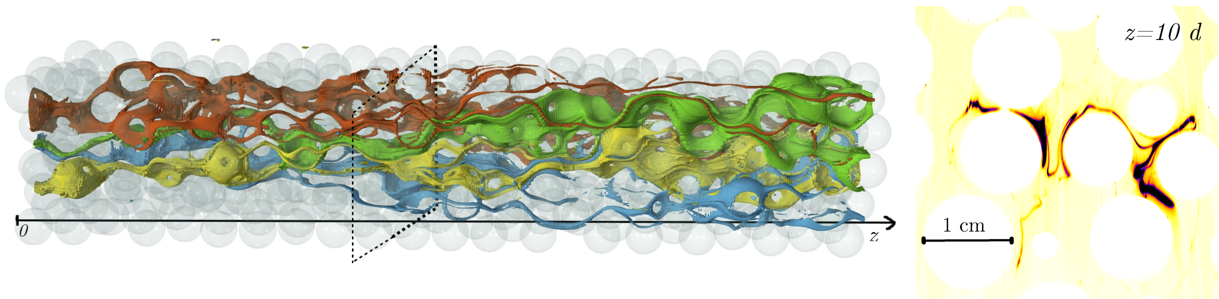

Figure 1: (Left) Experimental visualization of mixing and dispersion of 4 conservative tracers in a porous packed bed. Flow is in the direction of the z axis and tracers are injected continuously around $z = 0$. (Right) High resolution image of tracer concentration in the transverse plane (dashed lines in the left) showing filamentary structures.

A simple random walk model

We further discuss the possibility to relate the length ℓ of a filamentary structure as it gets advected along z to the intrinsic properties of the porous flow (the distribution of stretching rates).

The elongation of material lines advected by a vector field is by definition a multiplicative process [1]. Letting $\delta\ell$ be the length of an infinitely small material line element in the plane normal to z, then $s = \ln \delta\ell$ defines in turn an additive process. Owing to the random nature of the velocity field in a porous media, the stretching rate $\mathrm{d}s/\mathrm{d}z$ undergone by this infinitesimal material line in the transverse plane is a random variable. Assuming that the first moments of $\mathrm{d}s/\mathrm{d}z$ exist, the central limit theorem implies that s tends to a Gaussian distribution (with mean μ and variance σ^2) and thus that $\delta\ell = \exp s$ tends to the log-normal distribution.

Estimating the moment of the stretching rates (e.g. μ and σ^2) from the experiments is not trivial, since the measured variable ℓ consists of a sum of $N(z)$ independently evolving material line elements

$$\ell = \sum_{1=i}^{N(z)} \delta\ell_i, \tag{1}$$

each of the latter following a log-normal distribution. $N(z)$ depends on the initial length of the material line and the transverse spreading of the line as z grows.

In order to link the characteristics of ℓ to the individual stretching rates ds/dz, we formulate a simple random walk model for ℓ and derive its first moments. We finally estimate the average and variance of the stretching rate (μ, σ^2) in a 3D porous flow based on the experimentally measured filament length ℓ.

References

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