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## **Effect of Diffusion on Dispersion**

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### **Abstract**

We study dispersion in porous media by tracking movement of a swarm of solute particles through a physically representative network model. We developed deterministic rules to trace paths of solute particles through the network. These rules yield flow streamlines through the network comparable to those obtained from a full solution of Stokes' equation. In the absence of diffusion the paths of all solute particles are completely determined and reversible. We track the movement of solute particles on these paths to investigate dispersion caused by purely convective spreading at the pore scale. Then we superimpose diffusion and study its influence on dispersion. In this way we obtain for the first time an unequivocal assessment of the roles of convective spreading and diffusion in hydrodynamic dispersion through porous media. Alternative particle tracking algorithms that use a probabilistic choice of an out-flowing throat at a pore fail to quantify convective spreading accurately.

For Fickian behavior of dispersion it is essential that all solute particles encounter a wide range of independent (and identically distributed) velocities. If plug flow occurs in the pore throats a solute particle can encounter a wide range of independent velocities because of velocity differences in pore throats and randomness of pore structure. Plug flow leads to a purely convective spreading that is asymptotically Fickian. Diffusion superimposed on plug flow acts independently of convective spreading causing dispersion to be simply the sum of convective spreading and diffusion. In plug flow hydrodynamic dispersion varies linearly with the pore-scale Peclet number.

For a more realistic parabolic velocity profile in pore throats particles near the solid surface of the medium do not have independent velocities. Now purely convective spreading is non-Fickian. When diffusion is non-zero, solute particles can move away from the low velocity region near the solid surface into the main flow stream and subsequently dispersion again becomes asymptotically Fickian. Now dispersion is the result of an interaction between convection and diffusion and it results in a weak non-linear dependence of dispersion on Peclet number. The dispersion coefficients predicted by particle tracking through the network are in excellent agreement with the literature experimental data.

We conclude that the essential phenomena giving rise to hydrodynamic dispersion observed in porous media are (i) stream splitting of the solute front at every pore, thus causing independence of particle velocities purely by convection, (ii) a velocity gradient within throats and (iii) diffusion. Taylor's dispersion in a capillary tube accounts for only the second and third of these phenomena, yielding a quadratic dependence of dispersion on Peclet number. Plug flow in the bonds of a physically representative network accounts for the only the first and third phenomena, resulting in a linear dependence of dispersion upon Peclet number.

### **Introduction**

Traditionally, mixing in single-phase flow through a porous medium is quantified by a *dispersion coefficient* obtained from the flow-averaged ("cup-mixed") effluent concentration history (Lake 1989). The dispersion coefficient describes apparent mixing because it is averaged over the entire outlet and has contributions (in inseparable form) from (i) *convective spreading* (also called *mechanical dispersion*), caused by variations in path lengths and velocities of solute particles traveling along different streamlines and (ii) *molecular diffusion*.

Despite decades of research there remain questions about the nature and origin of dispersion. It is well accepted in the literature that convective spreading is orders of magnitude larger than diffusion. Is dispersion predominantly an artifact of convective spreading and diffusion categorically negligible (Coats *et al.* 2004), or does the role of diffusion become important in one limit or another?

The main objective of this paper is to explain core-scale dispersion from pore scale physics. We investigate dispersion by tracking the motion of a swarm of particles through granular porous medium. The flow paths through the medium are computed using a physically representative network model. We developed deterministic rules to trace solute particle's path