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Fluid Inertia and Symmetry-Breaking Generate Global Chaotic Mixing in Laminar Porous Media Flows

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Solute mixing in porous media is a fundamental process that controls various industrial and environmental processes. Since pore-scale flows are typically steady and laminar, solute mixing was thought to be largely driven by molecular diffusion. However, recent studies have shown that chaotic advection can emerge from 3D flow paths through the porosity [1, 2], strongly enhancing mixing as compared to 2D steady flow. In turn, we have observed that steady flows with weak inertia can also induce complex 3D flow structures in quasi-2D geometries, significantly enhancing local mixing [3-5]. The mechanism producing such enhancement is not yet fully understood.

In this study, we show that fluid inertia can induce global chaotic mixing in steady laminar flows through quasi-2D porous geometries. To do so, we use (1) Lagrangian particle tracking in direct numerical simulations of periodic geometries and (2) fluorescent solute imaging in microfluidic experiments. Numerical simulations were performed to study local fluid stretching rates and estimate Lyapunov exponents depending on the pore geometries. In turn, microfluidic experiments were performed to demonstrate the impact of Lagrangian chaos on scalar mixing rates, from creeping flow to inertial laminar flow regimes. Both periodic and random 2D porous geometries were investigated.

Our findings reveal that in periodic porous media, fluid inertia induces localized chaotic mixing, resulting in local enhancement of mixing and transverse dispersion. Mixing remains limited by the persistence of mixing barriers, as evidenced by Poincaré maps. In contrast, flow symmetry breaking, characteristic of random porous media, leads to a dramatic increase in fluid mixing and transverse dispersion due to the emergence of global chaotic flow. This behavior is marked by the disappearance of mixing barriers, highlighting the roles of fluid inertia and symmetry-breaking in driving global chaotic mixing.

The insights gained have far-reaching implications for optimizing natural and engineered processes where fluid mixing is critical, such as contaminant transport and carbon mineralization in fractured media, and biochemical reactions in micromixers.

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Primary authors: YANG, Weipeng (University of Minnesota); HEYMAN, Joris (CNRS); KANG, Peter (University of Minnesota)

Presenter: YANG, Weipeng (University of Minnesota)

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