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Fluid Stretching in Heterogeneous Porous Media as a Lévy Process

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Stretching and compression of material fluid elements is key for the understanding and quantification of the dispersion and mixing dynamics in heterogeneous porous media flows, because they represent the support of a transported solute. The elongation and compression of a material strip determine the mixing volume and mixing rate and thus the concentration content of a heterogeneous mixture. While linear and exponential elongation dynamics typical for shear and chaotic flows, respectively, are well understood, the mechanisms that lead toobserved power-law elongation in heterogeneous porous media are in general unknown. We cast the fluid deformation problem in streamline coordinates, which reveals that the principal elongation mechanism for non-helical steady flows is due to shear deformation and velocity fluctuations along the streamline. The impact of this coupling on the elongation dynamics is quantified within a continuous time random walk (CTRW) approach. The CTRW describes the movement of fluid particles in porous media flows through a random in both space and time, in which the transition time τ over a characteristic velocity length scale ℓ_c is coupled kinematically to streamline velocity v_s as $\tau = \ell_c/v_c$. In this framework, the elongation process isidentified as a coupled CTRW in which the elongation increment is related to the transition time through the velocity-shear coupling. For a broad distribution of transition, as found in strongly heterogeneous porous media, the elongation is a Lévy process. These dynamics describe a broad range of algebraic stretching behaviors with mean strip elongations $\langle \ell(t) \rangle \propto t^\nu$ with $1/2 \leq \nu < 2$. These findings have broad implications for the understanding and prediction of dilution and mixing in heterogeneous porous media flows.