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Impact of flow rate on chemical gradients and mixing dynamics in porous media

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Solute mixing mediated by flow in porous media plays a significant role in controlling reaction rates in subsurface environments. Due to incomplete mixing, solute concentrations are inhomogeneous at the pore scale in many practical cases. Incomplete mixing will limit local and upscaled reaction rates, rendering their prediction by classical Darcy scale reactive transport models inaccurate. The lamellar mixing theory was recently introduced to give a more accurate description of mixing dynamics. The theory uses a Lagrangian kinematic description of solute filaments as material lamellae, which undergo stretching and deformation in the surrounding flow field. This theory has successfully explained the experimentally-observed impact of Péclet number variation on single solute lamellae mixing in a two-dimensional simple shear flow field [1]. However, the applicability of these results to porous media, where pore-scale flow heterogeneity results in a complex fluid shear and stretching dynamics, remains an open question. To address it, we perform solute transport experiments in transparent, quasi-two-dimensional, soil analog models. These experiments investigate pore-scale solute dispersion and mixing under different flow rates, thus varying the Péclet number. We use Fluorescein as a conservative tracer and record its fluorescence intensity in monochrome images at fixed time intervals. We convert the fluorescence intensity to solute concentration fields and subsequently compute concentration gradients, which are indicators for solute mixing rates. Our images provide evidence for incomplete mixing at the pore-scale and show strong gradients transverse to the mean flow direction. The time evolution of the average value of the concentration gradients exhibits the theoretically-expected behavior: the gradients' magnitude initially increases due to advective compression and later decrease due to diffusion and lamellae coalescence. The time to reach the maximum gradient value, or the mixing time, decreases with Péclet. We show that the scaling of the mixing time with Péclet is identical to the theoretical prediction based on simple shear flow, indicating that the theory accurately captures the pore-scale mixing dynamics in the porous medium. However, the scaling of the maximum gradient magnitude as a function of the Péclet number shows a weaker dependency than that theory predicts. We explain this discrepancy by considering the role of lamellae coalescence, which decreases gradient values. We observe that lamellae coalescence depends on the distance traveled by the solute front in the porous medium, i.e., the number of grains the solute front has encountered. Thus, coalescence begins earlier for higher Péclet values, reducing their maximum gradient values. So, in conclusion, we adapt the lamellar mixing theory formulation from the simple shear flow behavior to a more general configuration characteristic of two-dimensional porous media.

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References

1. Souzy, M., Zaier, I., Lhuissier, H., Le Borgne, T. & Metzger, B. Mixing lamellae in a shear flow. J. Fluid Mech. 838, R3 (2018).

Time Block Preference

Time Block A (09:00-12:00 CET)

Participation

Online

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