Pore scale mixing and reactive transport under unsaturated conditions

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Concentration field of a conservative solute recorded during the continuous injection of the solute (at $c = 1$) into an unsaturated two-dimensional porous medium. White regions denote air bubbles.

Predicting the transport of chemical species through unsaturated porous media is still an open question. The spatial distribution of water and air clusters focuses the water flow onto narrow and complex flow paths, leaving large volumes of water trapped between air clusters, which makes the dispersion and mixing of solute elements strongly dependend on the saturation degree. We study the dependence on saturation of the longitudinal dispersion coefficient and temporal scaling properties of mixing in variably saturated porous media consisting of cylindrical grains inside a Hele-Shaw cell. The joint injection of the two phases provides a controlled homogeneous saturation. We simultaneously measure the flow velocity field, the spatial distribution of the two phases, and the tracer concentration field, and analyze the temporal behavior of the mean concentration gradient and scalar dissipation rate ; this behavior controls the potential for mixing-controlled chemical reactivity. For a continuous solute injection in unsaturated flows, we observe persistently large concentration gradients that decay slowly in time. We show that this effect is due to i) a drastic increase of the surface available to concentration gradients across the finger boundaries, ii) the mostly longitudinal orientation of the solute fingers, and iii) the near impossibility for these fingers to coalescence along the direction transverse to the mean flow, except at critical bottle necks formed between air clusters. For a pulse line injection we find that desaturation induces anomalous temporal scaling of the longitudinal dispersion (super-diffusive). In addition, the scalar dissipation rate first increases due to the advective stretching of material lines, and later decreases due to molecular diffusion. We propose an analytical model to explain the two mixing regimes and quantitatively predict the measured behavior without any fitting parameter.

References :

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