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Stabilization of immiscible displacement in fractures by controlling aperture variability and wettability

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We study immiscible fluid-fluid displacement in rough-walled fractures with a focus on the combined effect of wettability, the viscous contrast between the two fluids, and fracture surface topography on drainage patterns and interface growth. We have developed a model to simulate the dynamic displacement of one fluid by another immiscible one in a rough geological fracture; the model takes both capillary and viscous forces into account. Capillary pressures at the fluid-fluid interface are calculated based on the Young-Laplace equation using the two principal curvatures (aperture-induced curvature and in-plane curvature), while viscous forces are calculated by continuously solving the fluid pressure field in the fracture. The aperture field of a fracture is represented by a spatially correlated random field, with a power spectral density of the fracture wall topographies scaling as a power law, and a cutoff wave-length above which the Fourier modes of the two walls are identical. Results show that the model is able to produce displacement patterns of compact displacement, capillary fingering, and viscous fingering, as well as the transitions between them. Both reducing the aperture variability and increasing the contact angle (from drainage to weak imbibition) can stabilize the displacement due to the influence of the in-plane curvature, an effect analogous to that of the cooperative pore filling in porous media. Based on scaling analysis, we derive a relation between a dimensionless interface-smoothing parameter (N_{Sm}), defined by wettability and aperture variability, and the commonly used capillary number (N_{Ca}) and mobility ratio (M). This relation gives a surface in the three-dimensional (N_{Ca}–M–N_{Sm}) parameter space, which predicts the separation of the stable and unstable displacement regimes.

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