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Gravity-driven instability in fracture flows with miscible fluids of different densities

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Many important subsurface processes and applications, such as geologic carbon sequestration, enhanced geothermal system, and magma flow in dykes, involve flows of variable-density fluids in geologic fractures. Understanding the role of variable-density flow on transport, mixing, and geochemical reactions is essential for the prediction, design, and operation of the subsurface activities. In reality, vertical fractures are common, and flow and transport in vertical or inclined fractures will determine the integrity of caprocks. However, the effects of density contrasts on flow and mixing in vertical fractures have rarely been studied.

In this study, we combine visual laboratory experiments and direct three-dimensional (3D) numerical simulations to study the effects of fracture inclination angle (orientation relative to gravity), flow inertia, and density contrasts between fluids on the spatiotemporal distribution of miscible fluids in a fracture. Two miscible fluids with different densities are injected through two inlets at the bottom of the fracture and flowed out from the outlet at the top of the fracture. The density contrast between two injection fluids results in the lighter fluid being confined to a narrow path, which we term "runlet", and the instability of this runlet is observed in both visual lab experiments and 3D numerical simulations. We investigate the underlying mechanisms triggering the instability in variable-density fracture flows by systematically conducting numerical simulations for various combinations of flow rates, density contrasts, and fracture inclination angles. We first identify critical stagnation points that control the instability of the runlet through streamline and flow topology analysis. We then elucidate the effects of fluid stretching and mixing on the evolution of critical stagnation points by analyzing the spatiotemporal evolution of stretching and mixing measures. Our results show that the runlet is formed by the complex interplay between the density contrast, inertia effects, and mixing, and the runlet instability is controlled by 3D vortices.

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References

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