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Effects of fluid density and inertia on solute transport at fracture intersections: Visual laboratory experiments and pore-scale numerical simulations

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Flow and transport in fractured media are governed by complex interactions between geological heterogeneity and fluid properties. In subsurface systems, fluids with different densities often coexist, leading to density-driven flow that can impact flow and transport. Additionally, in fractured systems where high flow velocities are common, fluid inertia can further influence transport dynamics by inducing vortices, creating mixing hotspots, and enhancing reaction rates at fracture intersections. Understanding the interplay between these processes is crucial for subsurface applications, including saltwater intrusion, enhanced geothermal systems, and geologic carbon sequestration. While previous studies have explored either density-driven flow or inertia effects on solute transport, the combined influence of these factors on solute transport in fracture networks remains poorly understood. This study combined pore- to network-scale visualization experiments and numerical simulations to investigate how fluid density contrast coupled with fluid inertia governs solute transport and retention in fractured media.

At the network scale, artificial fracture networks were constructed from transparent acrylic blocks to enable 3D visualization of transport processes. A fluorescent dye, with a density 21% denser than the ambient water, was injected as a tracer. We observed persistent vortices emerging at vertical fractures near fracture intersections, leading to localized solute trapping within the network. To further examine the underlying mechanisms of this trapping behavior, we developed a bench-top-scale visualization apparatus focused on a single fracture intersection. This apparatus, constructed from clear acrylic sheets, features two smooth horizontal fractures connected by a vertical fracture, with a constant aperture of 0.5 cm. A series of controlled experiments were conducted to investigate the roles of density contrast, fluid inertia, and flow imbalance on solute trapping. Image analysis was performed to quantify tracer concentration evolution within the vertical fracture and breakthrough curves in the horizontal fractures.

The experimental results demonstrated that the combination of density contrast and inertia effects leads to enhanced solute trapping. The density contrast allows the dye to sink into the vertical fracture, and vortices induced by fluid inertia trap the tracer within the vertical fracture, significantly enhancing solute retention. The localized vortices emerge at the base of the vertical fracture, trapping the dense tracer in recirculation zones over an extended period. Maximum solute trapping was observed when the flow rate in the bottom horizontal fracture was 10% higher than that in the top horizontal fracture, effectively balancing the downward flow of the denser fluid. This emphasizes the critical interplay between density effects and inertia effects, which significantly control solute retention at fracture intersections. Pore-scale numerical simulations reproduced the localized trapping observed in experiments and revealed detailed insights into the key processes governing solute transport, including the emergence of recirculation zones, the dynamics of vortices affected by density effects, and the influence of flow imbalance on velocity field leading to maximum solute retention. Our results highlight the importance of small-scale processes, such as vortex-induced trapping of dense fluids, in controlling flow and transport dynamics at larger scales. These insights provide valuable fundamental understanding relevant to various subsurface engineering applications.

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References

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