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Unstable dynamics of two-phase displacement in porous media associated with hydrogen storage

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Hydrogen storage in saline aquifers offers a promising large-scale, long-term strategy for renewable energy storage. Compared to conventional CO2 geological storage, hydrogen injection introduces unique challenges due to its ultra-low viscosity and density, high rock reactivity, and microbial driven consumption [1]. In this work, we set aside bio-geo-chemical reactions to focus on the first-order dynamic behavior of the system—hydrogen plume migration during and after injection. Its complexity arises from two potential mechanisms: (1) the large viscosity contrast between hydrogen and brine, which can drive viscous fingering, and (2) the density contrast that may promote gravity segregation. Recent core-scale experiments [2, 3] have shown that these combined effects can induce strong flow channeling and significant hydrogen trapping, highlighting the need to systematically investigate the interplay among capillary, viscous, and gravitational forces across different scales.

To address this gap, we present a three-dimensional dynamic network model for hydrogen–brine displacement, where the solid matrix is represented by realistic rock microstructures, and a two-pressure formulation is employed to resolve corner flow in detail. While this framework was originally built for a strong drainage regime [4, 5], we extend it to incorporate rich pore-scale invasion events that account for different contact angles. We inject a less viscous and less dense fluid vertically into a brine-saturated matrix for a prescribed time, then stop the injection to observe the subsequent fluid migration. We study the displacement patterns at three dimensionless parameters—capillary number, bond number, and viscosity ratio—which are rationalized via linear stability analysis. Furthermore, by comparing our results with core-scale experiments, we reveal the essential physics governing unstable displacements and provide guidance for reservoir-scale simulations of hydrogen storage.

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Primary author: QIU, Yu (Stanford University)

Co-author: TCHELEPI, Hamdi

Presenter: QIU, Yu (Stanford University)

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