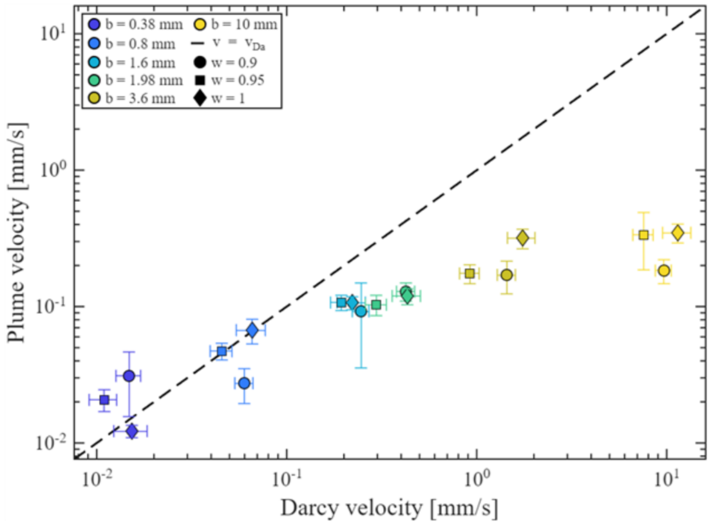
Transition from quasi-2D to 3D regimes in convective dissolution under confinement

Paul Fruton[1], Filippo Mauri[1], Stefano Castellini[1], Marina Carpineti[1], Alberto Vailati[1]

[1]Università Degli Studi Di Milano, Milano, Italy

Convective dissolution is a key mechanism controlling the efficiency and long-term security of geological CO_2 sequestration, as it enhances the downward transport of dissolved CO_2 and limits leakage risks. Within a porous medium, dissolution of CO_2 into the underlying brine forms a denser boundary layer which, above a critical density gradient, becomes gravitationally unstable and generates downward plumes. This process has been extensively studied in Hele-Shaw cells, whose geometric confinement provides a convenient analogue of porous media with direct optical access. However, the validity of this analogy remains debated. In particular, the parameter ε^2Ra, with ε the anisotropy ratio and Ra the Rayleigh-Darcy number, has been proposed to distinguish quasi-two-dimensional and three-dimensional regimes, with a transition at $\varepsilon^2\text{Ra} \approx 1$, without exploring extensively the transition behaviour[1,2].



Here, we experimentally investigate this transition using a water–propylene glycol system exhibiting a non-monotonic density profile, which simulates the behaviour of the CO_2-brine system and enables the development of gravitational instabilities. The cell gap thickness, b, is varied from 0.38 mm to 10 mm to systematically probe the role of geometric confinement and explore a large range of Rayleigh-Darcy numbers. Flow dynamics are visualized via shadowgraphy, allowing measurements of plume velocities, characteristic widths, spatial distribution, and mixing rates.

The core analysis is based on confronting the experimental velocity of plumes with theoretical models (Darcy, Darcy-Brinkmann, 3D Stokes). Our results identify a transition from a Darcy-like regime to one in which transversal three-dimensional effects become significant. The mean plume velocity follows Darcy scaling at strong confinement ($b \lesssim 0.8$ mm) and deviates from the model when the confinement is reduced ($b \gtrsim 1.6$ mm).

Further insight is obtained from the analysis of the plume width, δ. We find that the ratio δ/b decreases below unit when $\varepsilon^2\text{Ra} > 1$, indicating that plumes no longer span the full gap and that confinement across the thickness starts to disappear. The threshold provides a consistent way to separate the datasets into distinct regimes. Below it, the transport is well described by Darcy-based scaling, while above it, the data are better described by models accounting for three-dimensional effects. In particular, the Sherwood number exhibits distinct scaling behaviours in the two regimes, highlighting the change in the dominant transport mechanism.

These findings demonstrate that geometric confinement plays a fundamental role across all regimes and set quantitative limits on the validity of Hele-Shaw models as analogues of porous media.

References:

[1] Paoli, M. De, Alipour, M. Soldati, A. How non-Darcy effects influence scaling laws in Hele-Shaw convection experiments. (2020) doi:10.1017/jfm.2020.229.

[2] Letelier, J. A., Mujica, N. Ortega, J. H. Perturbative corrections for the scaling of heat transport in a Hele-Shaw geometry and its application to geological vertical fractures. 746–767 (2019) doi:10.1017/jfm.2019.3.