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Convective mixing in confined porous media: pore-scale experiments, simulations and modelling

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We consider the process of convective dissolution in homogeneous and isotropic porous media. The flow is unstable due to the presence of a solute that induces a density difference responsible for driving the flow. The mixing dynamics is thus driven by a Rayleigh–Taylor instability.

Methodology

We investigate the flow at the scale of the pores using Hele-Shaw type experiment with bead packs (Figure 1), two-dimensional direct numerical simulations (Figure 2), and physical models. Experiments and simulations have been specifically designed to mimic the same flow conditions, namely matching porosities ($\phi = 0.37$), high Schmidt numbers ($Sc \approx 500$) and a linear dependency of the fluid density with the solute concentration. In addition, the solid obstacles of the medium are impermeable to fluid and solute.

Results

We characterise the evolution of the flow via the mixing length, which quantifies the mixing region's extension. It grows in time proportionally to the buoyancy velocity U, and it is used to validate the simulations. Finally, we analyse the dissolution dynamics of the system, quantified through the mean scalar dissipation, and several mixing regimes are observed (Figure 4).

Modelling

Initially, the evolution is controlled by *diffusion*, which produces solute mixing across the initial horizontal interface. When the interfacial diffusive layer is sufficiently thick, it becomes unstable, forming finger-like structures and driving the system into a *convection-dominated* phase. Finally, when the fingers have grown sufficiently to touch the horizontal boundaries of the domain, the mixing reduces dramatically due to the absence of fresh unmixed fluid (*convective shutdown* phase).

Conclusions

With the aid of simple physical models, we explain the physics of the results obtained numerically and experimentally. The solute evolution presents a self-similar behaviour, and it is controlled by *different length scales* in each stage of the mixing process, namely the length scale of diffusion, the pore size and the domain height.

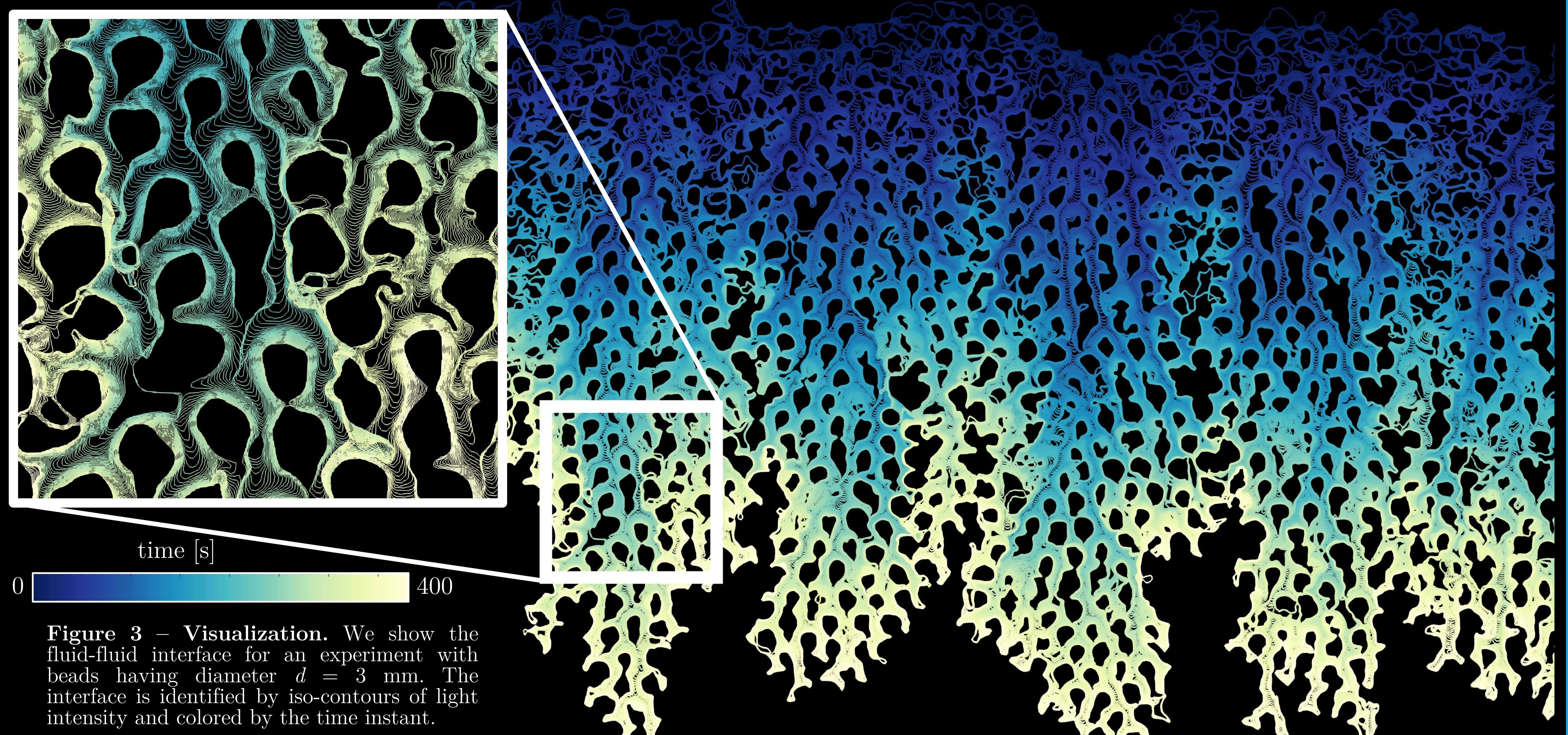


Figure 3 – Visualization. We show the fluid-fluid interface for an experiment with beads having diameter $d = 3$ mm. The interface is identified by iso-contours of light intensity and colored by the time instant.

Figure 1 - Experiments. The Hele-Shaw cell is filled with beads and two fluids from the upper and lower valves. A gate keeps the fluids separated. After the gate is extracted, the cell is rotated about the x-axis, the fluids are in an unstable configuration (heavy solution on top of the lighter fluid) and the experiment starts.

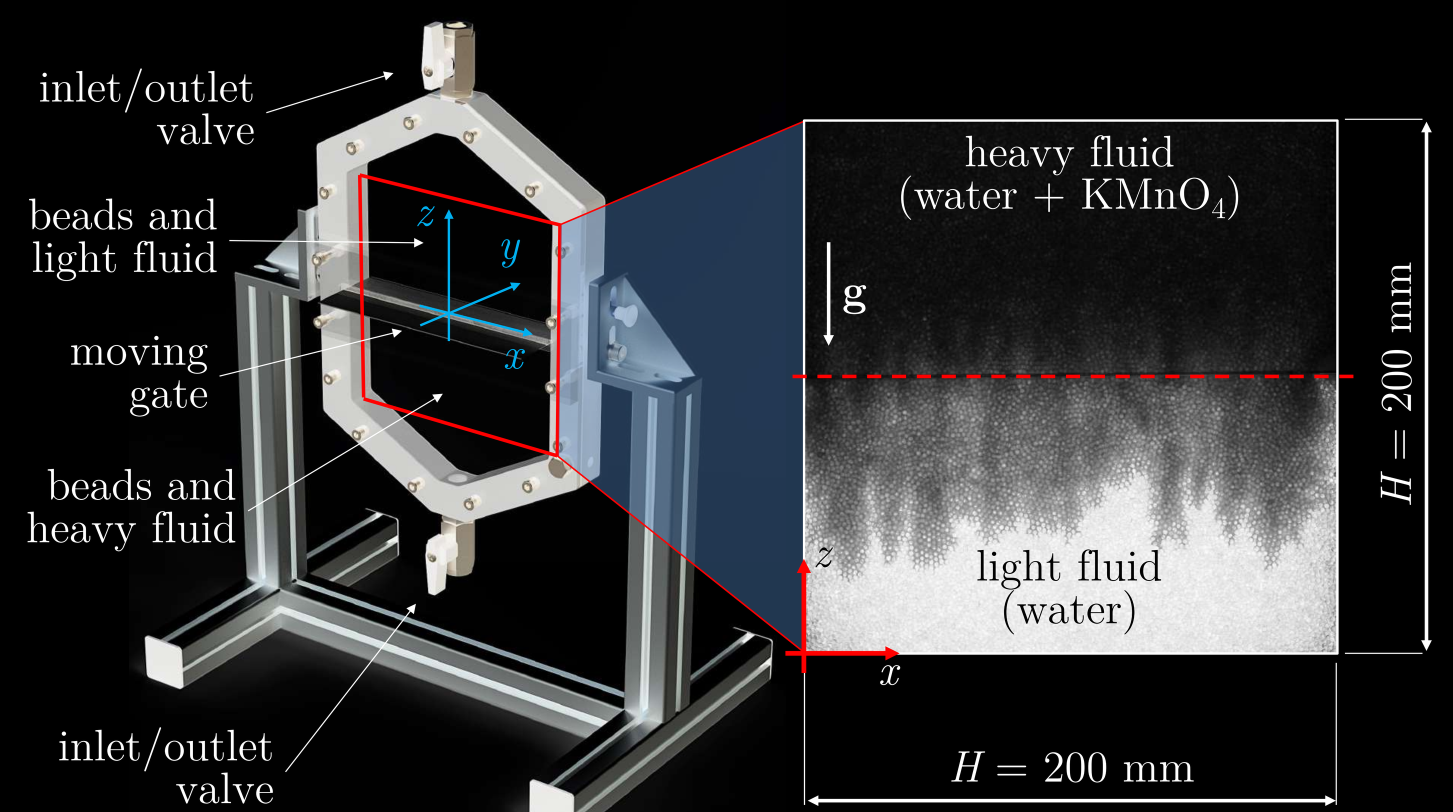


Figure 2 - Simulations. Finite-differences + IBM are used to simulate the flow. The medium consists of an hexagonal pattern of solid circles (diameter d). Here we show a simulation snapshot with $H/d = 70$, with solute concentration varying between low ($C = 0$, green) and high ($C = C_0$, black) values.

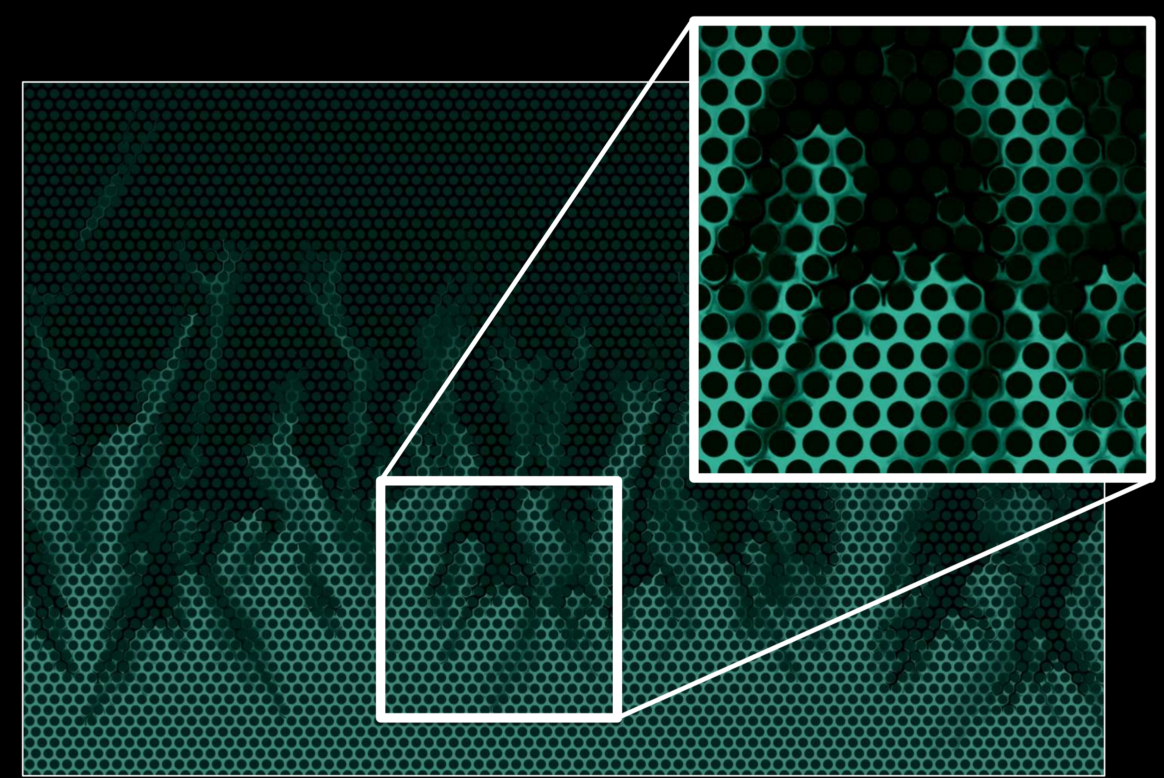
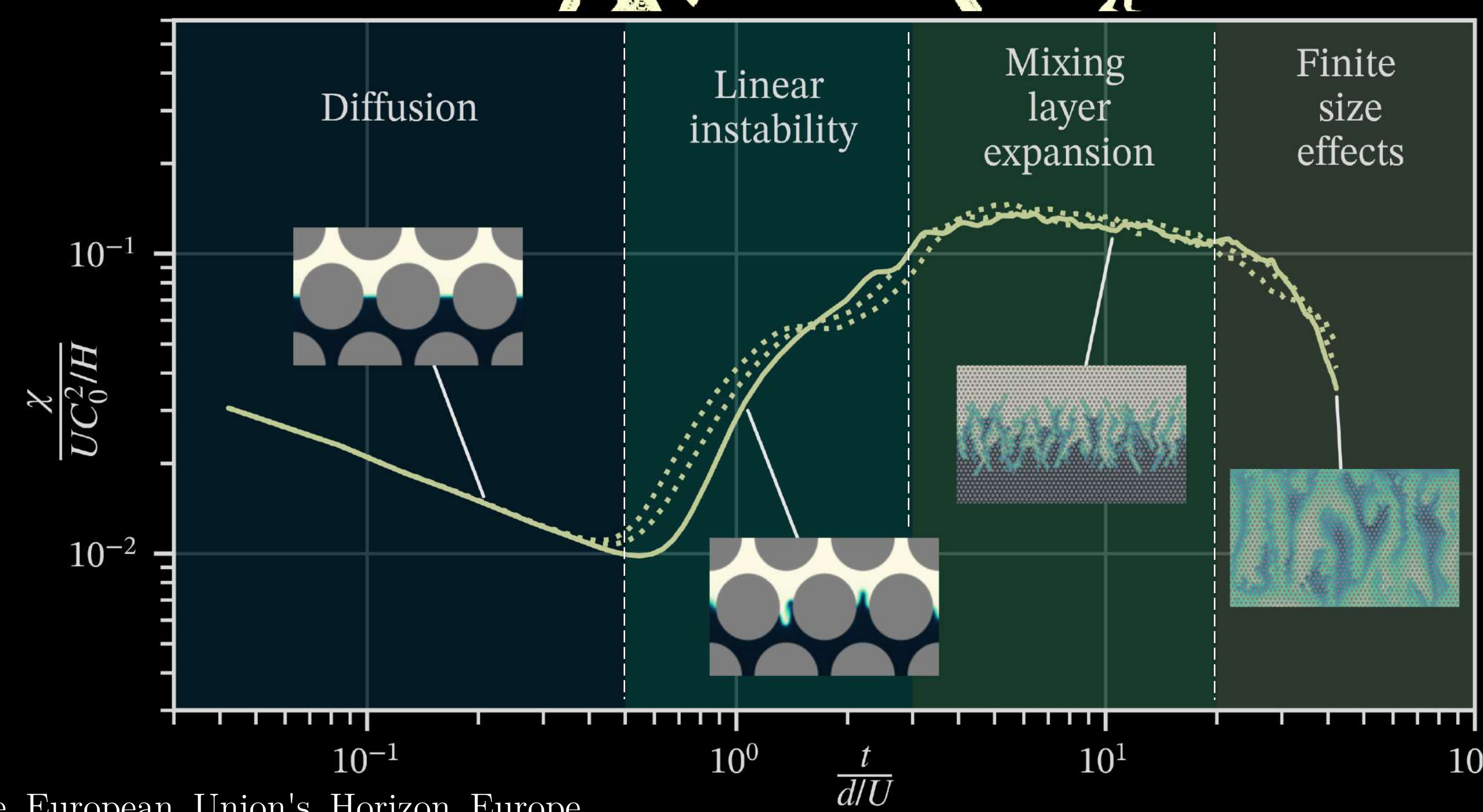


Figure 4 – Modelling. Evolution of the mean scalar dissipation (χ) over time (t). The time is made dimensionless with (d/U). Three different simulations are shown, corresponding to the same flow parameters and different arrangements of the obstacles (regular and perturbed patterns, corresponding to solid and dotted lines, respectively). Concentration fields in different phases of the process are also shown (regular pattern).



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References
De Paoli, M., Howland, C. J., Verzicco, R., & Lohse, D. (2024). Towards the understanding of convective dissolution in confined porous media. *J. Fluid Mech.*, 987, A1.