IMPERIAL

Direct pore-scale simulation of the origins of intermittency in multiphase flow

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07/01/2026

Motivation
Non-linear Flow Regimes

OpenFOAM Porefoam2f

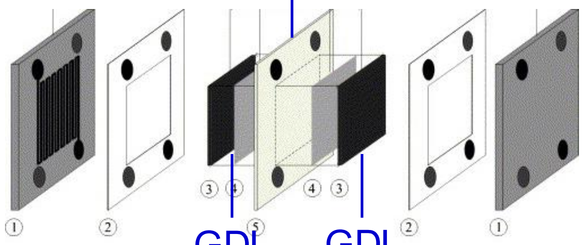
Direct Numerical Simulation of Incompressible Two-Phase Flow on 3D Images of Porous Media Using the OpenFOAM Finite-volume Library

$$Re = \frac{Inertial}{Viscous} = \frac{\rho v d}{\mu}$$

1. Hydrogen Storage: $Re^{max} \sim 10^1$

   High injection/withdrawal rates → recovery efficiency degrades due to gas flow instabilities [1]

2. Gas Diffusion Layers (GDLs): $Re^{max} \sim 10^3$ [2]
3. Packed Beds: $Re^{max} \sim 10^4$ [3]



[1] P. Jadhawar and M. Saeed, "Optimizing the operational efficiency of the underground hydrogen storage scheme in a deep North Sea aquifer through compositional simulations," Journal of Energy Storage, vol. 73, p. 108832, 2023, doi: https://doi.org/10.1016/j.est.2023.108832.

[2] J. Park and X. Li, "An experimental and numerical investigation on the cross flow through gas diffusion layer in a PEM fuel cell with a serpentine flow channel," Journal of Power Sources, vol. 163, no. 2, pp. 853–863, 2007, doi:https://doi.org/10.1016/j.jpowsour.2006.09.083

[3] F. Suja and T. Donnelly, "Reynolds Number Calculation Method for Aerobic Biological Porous Packed Reactors," vol. 18, Jan. 2006.

Flow regime affects network characteristics e.g. permeability.

Onset of Non-Linearity in Multiphase Flow

Macroscopic Viscous vs Capillary Effects

[5] A. Anastasiou, I. Zarikos, A. Yiotis, L. Talon, and D. Salin, "Steady-State Dynamics of Ganglia Populations During Immiscible Two-Phase Flows in Porous Micromodels: Effects of the Capillary Number and Flow Ratio on Effective Rheology and Size Distributions," Transport in Porous Media, vol. 151, pp. 1–25, Jan. 2024, doi: 10.1007/s11242-023-02041-0.

$$Ca = \frac{Viscous}{Capillary} = \frac{\mu q}{\sigma} \sim 10^{-3}|_{GDL}$$

μ = viscosity

q = Darcy velocity

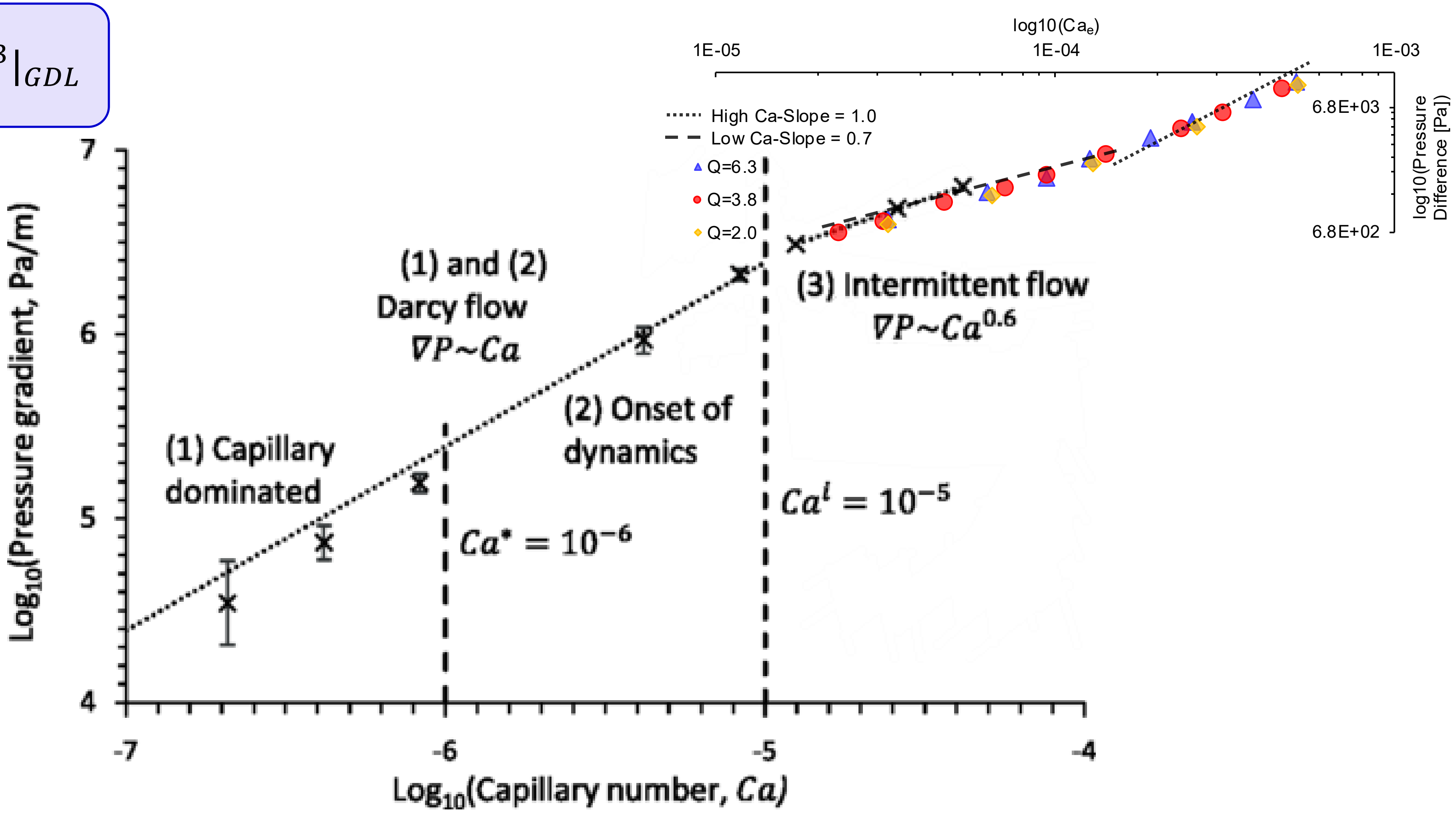
σ = interfacial tension

$\nabla P \propto Ca$ linear in Darcy

Experimentally:

Non-linearity begins at the Intermittent Flow Regime.

Earlier than onset of Forchheimer regime



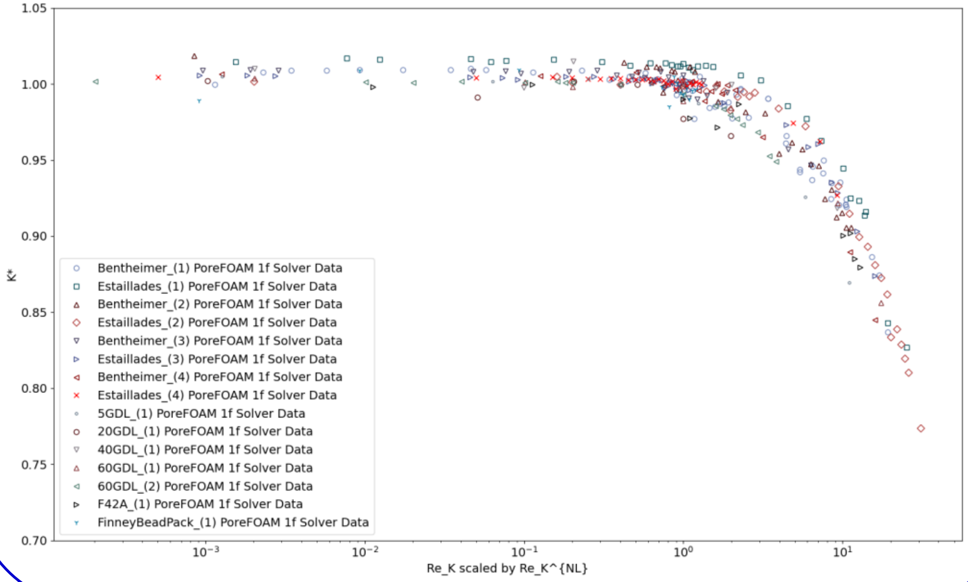
[4] Y. Gao, Q. Lin, B. Bijeljic, and M. J. Blunt, "Pore-scale dynamics and the multiphase Darcy law," Phys. Rev. Fluids, vol. 5, no. 1, p. 013801, Jan. 2020, doi: 10.1103/PhysRevFluids.5.013801.

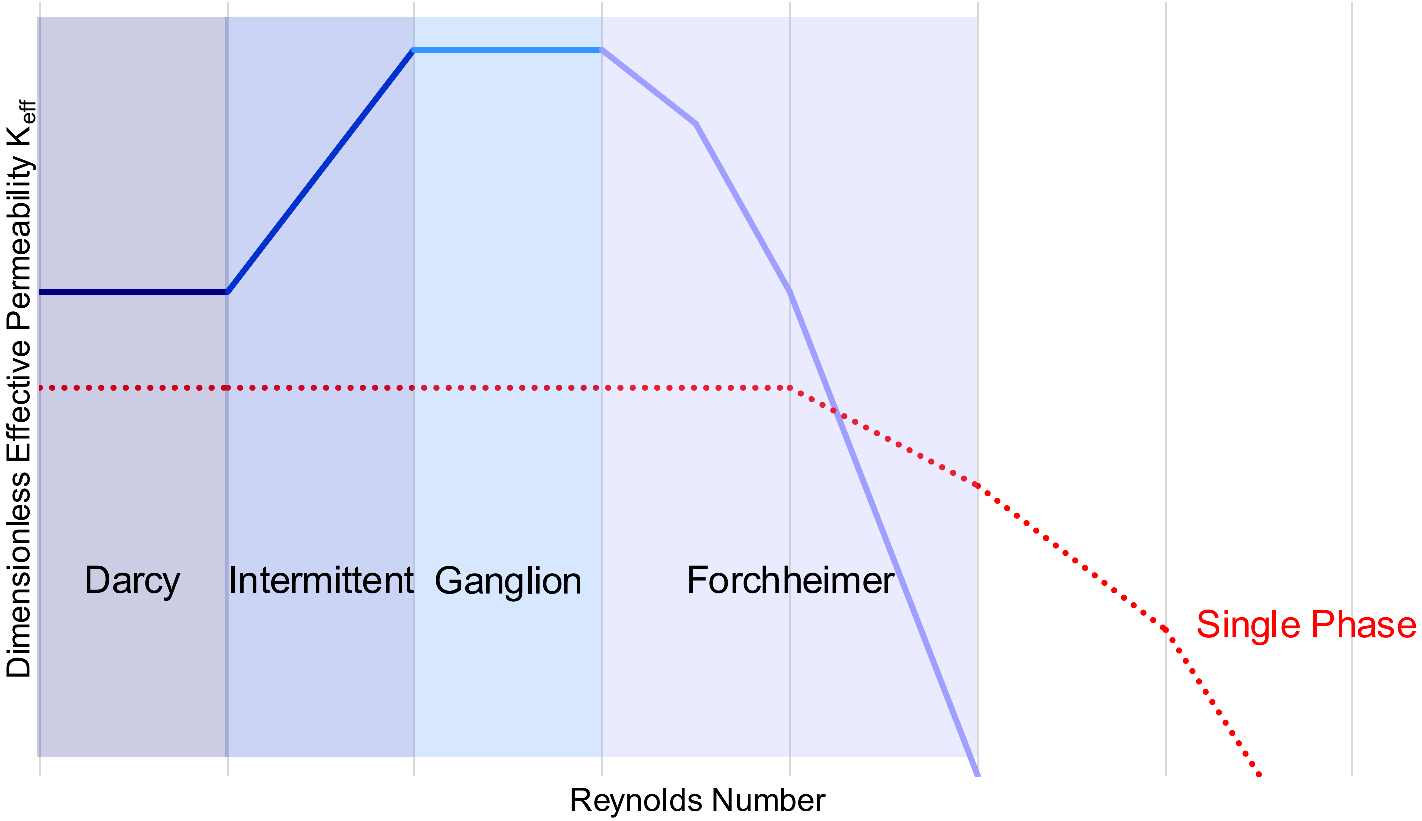
Onset of Non-Linearity in Multiphase Flow

Universal Collapse: Macroscopic Permeability Trends

Expect **effective** dimensionless permeability K* to increase in the Intermittent Flow regime.

Cf. Single-phase K* universal collapse:





Onset of Non-Linearity in Multiphase Flow

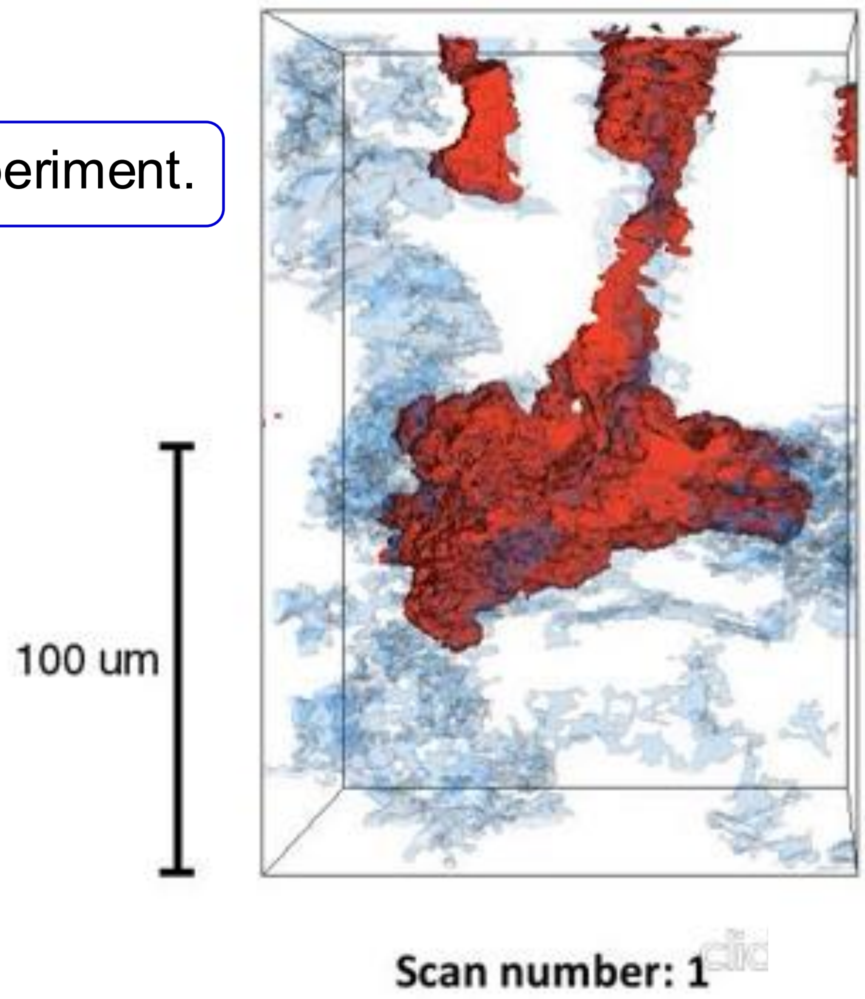
Pore-Scale Intermittency

Intermittent effect observed in fixed region of space in experiment.

Problem

Quantifying and predicting the intermittent effect at the pore-scale via DNS

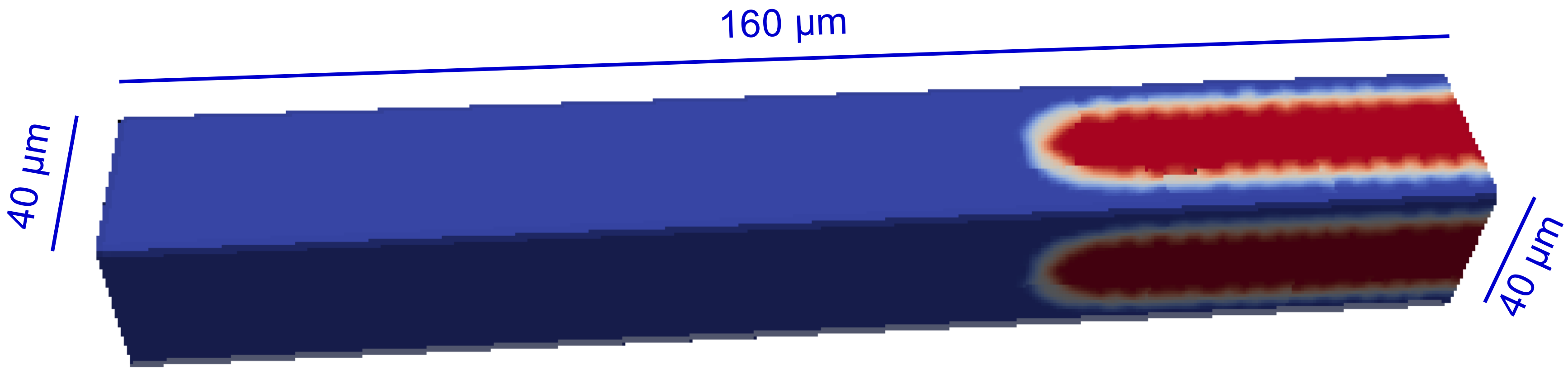
1. Validate the observed early onset of non-linearity.
2. Identify specific intermittent flow pathways.

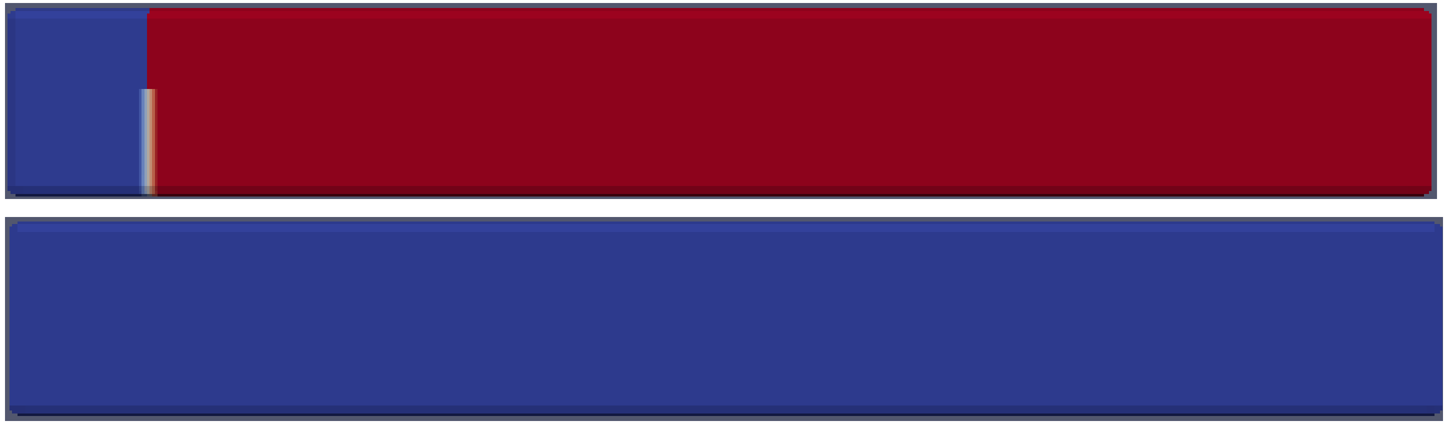


[6] C. Spurin et al., "The development of intermittent multiphase fluid flow pathways through a porous rock," Advances in Water Resources, vol. 150, p. 103868, 2021, doi: https://doi.org/10.1016/j.advwatres.2021.103868.

Onset of Non-Linearity in Multiphase Flow

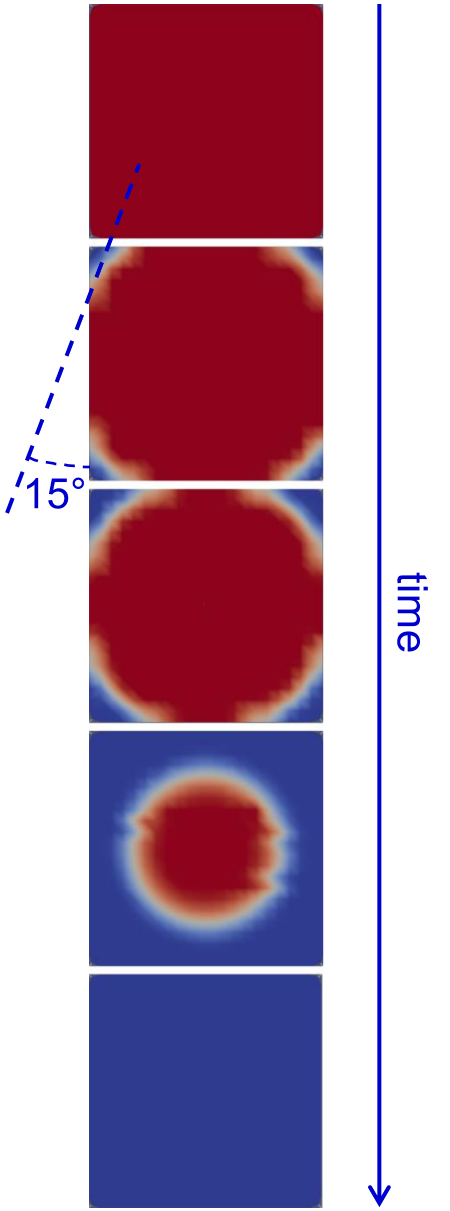
Immiscible Liquid-Liquid Displacement in a Micro-Capillary





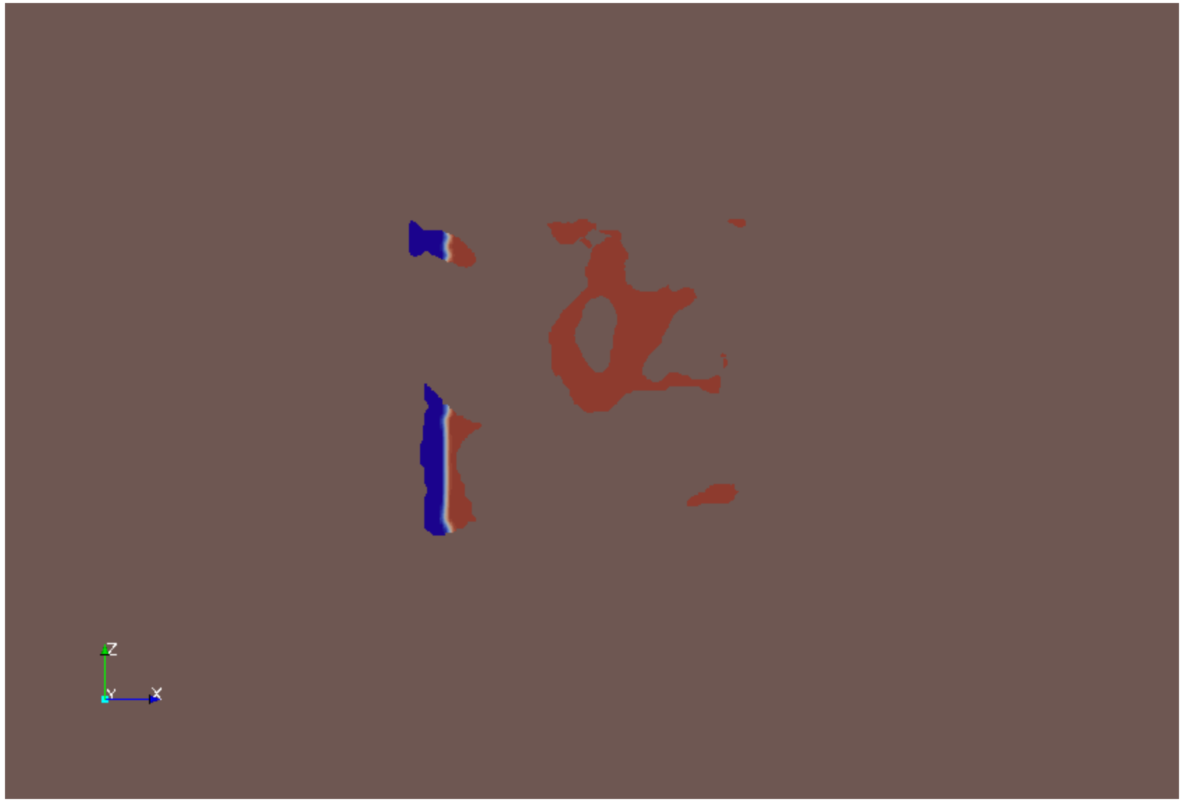
Injection rate 10^5 µm/s

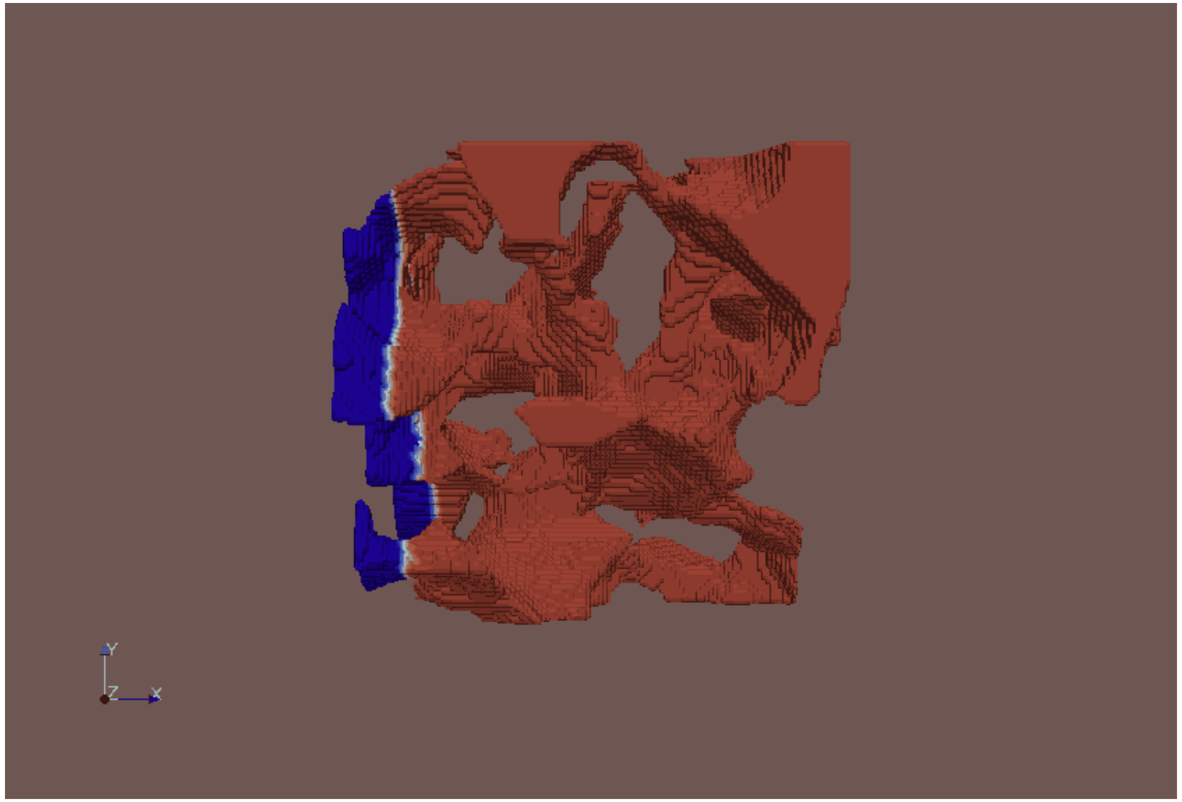
Injection rate 850 µm/s



Different flow regimes trigger different flow behaviour mechanisms

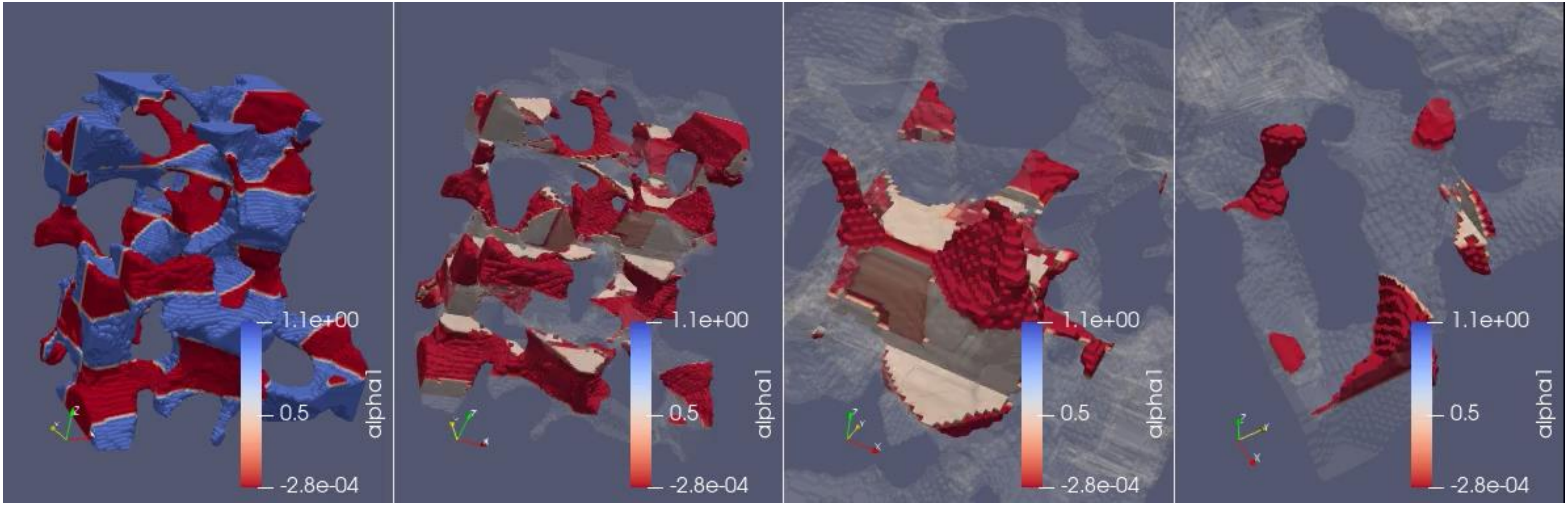
Onset of Non-Linearity in Multiphase Flow
Immiscible Displacement in Bentheimer Sandstone





Network-like structural connections in the pore-space complicate transient flow behaviour.

Onset of Non-Linearity in Multiphase Flow
Two-Phase Co-Injection in Bentheimer Sandstone



Two-phase flow transitions to steady state behaviour with clear intermittent regions.

Next Steps

Problem

Quantifying the effect of intermittency at the pore-scale via DNS

- Build confidence in DNS 2f-solver accuracy
- Quantify macroscopic behaviour to pin down intermittent regime cf. experiment
- Compute effective flow properties and quantify their dependence on pore geometry and flow rate.

Direct Pore-Scale Simulation of Rate Effects in Single and Multiphase Flow
07/01/2026

Summary

Problem

Quantifying the effect of intermittency at the pore-scale via DNS

Outcomes:

1. Gain insight into the physics of the effect of intermittency.
2. Significantly reduce computational costs while maintaining the predictive power over essential flow behaviour.

Further implications for optimising designs of manufactured media, e.g. GDLs

Thank you

Direct pore-scale simulation of the origins of intermittency in multiphase flow
07/01/2026

Appendix: Motivation
Rate Effects

Hydrogen Storage:

$Re^{max} \sim 10^1$

Reported maximum injection rate

$\mathrm{Q} = 25\ \mathrm{MMSCF/d}$

[1] M. Delshad, Y. Umurzakov, K. Sepehrnoori, P. Eichhubl, and B. R. Batista Fernandes, "Hydrogen Storage Assessment in Depleted Oil Reservoir and Saline Aquifer," Energies, vol. 15, no. 21, 2022, doi: 10.3390/en15218132.

in SI units $\mathrm{Q} = 8.195\ \mathrm{m}^3/s$

Average velocity in reservoir

$$v = \frac{Q}{\varphi A} \approx \frac{8}{0.2 \cdot 100} = 0.4\ \mathrm{m}/s$$

Reynolds number

$$Re = \frac{\rho v d}{\mu} \approx \frac{0.09 \cdot 0.4 \cdot 10^{-5}}{8.9 \cdot 10^{-6}} = 40$$

Gas Diffusion Layers (GDLs):

$Re^{max} \sim 10^3$

Example oxygen velocity

$\mathrm{v} = 15\ \mathrm{m}/s$

[2] J. Park and X. Li, "An experimental and numerical investigation on the cross flow through gas diffusion layer in a PEM fuel cell with a serpentine flow channel," Journal of Power Sources, vol. 163, no. 2, pp. 853–863, 2007, doi: https://doi.org/10.1016/j.jpowsour.2006.09.083.

Effective velocity

$$v_e = \frac{v}{\varphi} \approx \frac{15}{0.5} = 30\ \mathrm{m}/s$$

Reynolds number

$$Re = \frac{\rho v_e d}{\mu} \approx \frac{1.2 \cdot 30 \cdot 10^{-3}}{1.8 \cdot 10^{-5}} = 2 \cdot 10^3$$

Packed Beds:

$Re^{max} \sim 10^4$

Example organic loading rate in aerobic biological reactor

$\mathrm{Q} = 13.39\ \mathrm{L/d}$

[3] F. Suja and T. Donnelly, "Reynolds Number Calculation Method for Aerobic Biological Porous Packed Reactors," vol. 18, Jan. 2006.

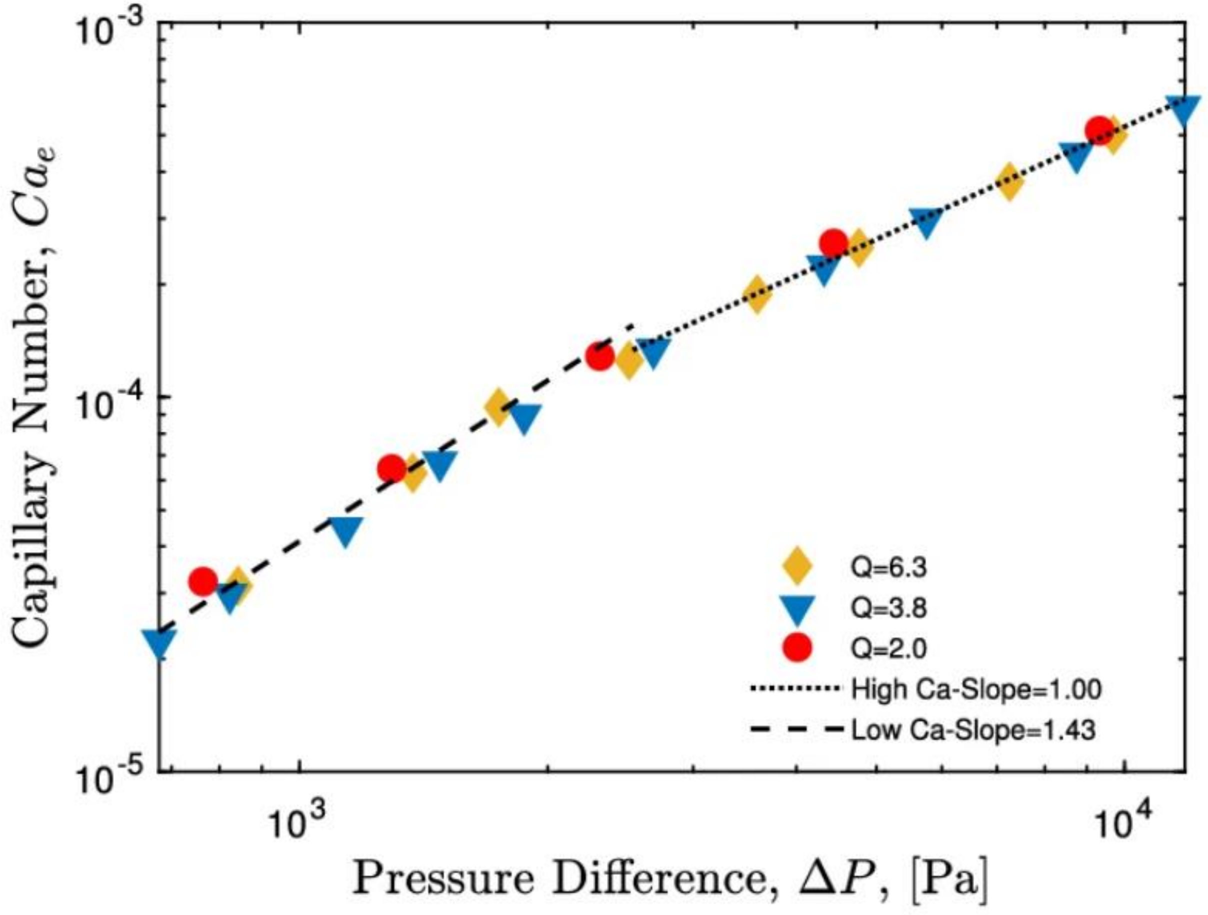
in SI units $\mathrm{Q} = 1.55 \cdot 10^{-4}\ \mathrm{m}^3/s$

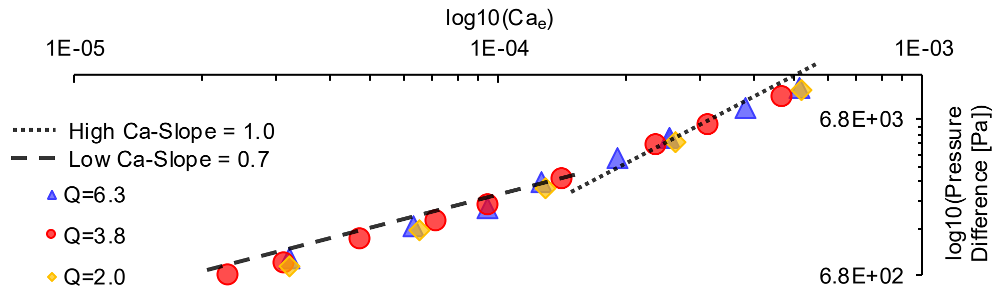
Reynolds number

$$Re = 19500$$

Appendix: Onset of Non-Linearity in Multiphase Flow

Macroscopic Viscous vs Capillary Effects





[5] A. Anastasiou, I. Zarikos, A. Yiotis, L. Talon, and D. Salin, "Steady-State Dynamics of Ganglia Populations During Immiscible Two-Phase Flows in Porous Micromodels: Effects of the Capillary Number and Flow Ratio on Effective Rheology and Size Distributions," Transport in Porous Media, vol. 151, pp. 1–25, Jan. 2024, doi: 10.1007/s11242-023-02041-0.