

Learning from Experiments: Imaging, Simulation, and Discrepancy in Porous Media Flow

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Modern laboratory experiments of flow in porous media produce unprecedented volumes of spatio-temporal data. The challenge is no longer obtaining observations, but converting observations into scientific understanding. This raises a fundamental question: how much can we learn from a single experiment, and when do we need many?

This talk presents a computational perspective developed through the FluidFlow ecosystem, a meter-scale laboratory platform for repeatable multiphase flow experiments in heterogeneous porous media [1]. I discuss how quantitative physical information can be extracted from high-resolution images while accounting for the multi-scale nature of porous media flow. By converting observations into continuum-scale quantities [2], experimental data can be directly compared with Darcy-scale models for flow, transport, and geological CO₂ storage, enabling model validation [3], benchmark studies [4,5], and digital-twin workflows [6].

While individual experiments provide insight into specific flow realizations, ensembles of repeated experiments reveal that variability is itself a measurable and informative feature of the system. This challenges validation against a single realization and motivates a transition from model fitting to discrepancy analysis. The central question becomes: what can the differences between experiments and simulations tell us about missing physics, uncertainty, and model limitations?

To explore this question, I will discuss recent work on optimal-transport-based metrics for quantifying discrepancy between observed and simulated flow patterns. Together with benchmark studies, experimental ensembles, and emerging scientific machine learning approaches, these methods offer a framework for transforming model-experiment mismatch into quantitative insight.

[1] Fernø, M. A., et al. "Room-scale CO₂ injections in a physical reservoir model with faults." *Transport in Porous Media* 151.5 (2024): 913-937.

[2] Nordbotten, Jan Martin, et al. "DarSIA: An open-source Python toolbox for two-scale image processing of dynamics in porous media." *Transport in Porous Media* 151.5 (2024): 939-973.

[3] Both, J. W., Brattekkås, B., Keilegavlen, E., Fernø, M., & Nordbotten, J. M. (2024). High-fidelity experimental model verification for flow in fractured porous media. *InterPore Journal*, 1(3), IPJ271124-6.

[4] Flemisch, Bernd, et al. "The FluidFlow Validation Benchmark Study for the Storage of CO₂:" *Transport in Porous Media* 151.5 (2024): 865-912.

[5] Nordbotten, Jan M., et al. "Benchmarking CO₂ Storage Simulations: Results from the 11th Society of Petroleum Engineers Comparative Solution Project." *International Journal of Greenhouse Gas Control* 148 (2025): 104519.

[6] Keilegavlen, Eirik, et al. "PoroTwin: A Digital Twin for a FluidFlow Rig: E. Keilegavlen et al." *Transport in Porous Media* 151.5 (2024): 1241-1260.