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Preface to the Special Issue on FluidFlower: A Meter-Scale Experimental Laboratory for Geological CO_2 Storage

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This special issue is home to the "FluidFlower Validation benchmark study" Flemisch et al. (2023) and 13 associated papers. The central theme is the FluidFlower, which is on the one hand an experimental rig and, on the other hand, an opportunity caused by a unique set of circumstances.

1 Background

The original idea of constructing the FluidFlower was to construct an experimental laboratory that was well suited to both scientific research and public outreach. Indeed, a core principle was to allow for demonstrating the key physical mechanisms underpinning geological CO_2 storage to the public in what can be perceived as a realistic setting. This motivated the design of a relatively large experiment (about 3 by 2 m), with a transparent glass plate, and where pH sensitive dye was used to mark the CO_2 concentration in the water phase. With these dimensions, some geological complexity could be included in the experiment, and

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the use of high-permeable unconsolidated sands reduced the timescales to hours and days, as opposed to the years and centuries of relevance at field conditions.

The science part of the FluidFlower study was facilitated by the serendipitous arrival of the Covid-19 pandemic. We realized that the construction of the FluidFlower was at a scale and purpose which was quite unique, and that the travel restrictions imposed by Covid-19 allowed us to limit the insight non-local scientists would have in the experiments we conducted. This motivated the design of, and call for participation in, a forecasting study during spring 2021—and to our great fortune, good colleagues from around the globe agreed to participate.

The main part of the study took place from early fall 2021 through April 2022, and during this process, it quickly became clear that there was much more to be said about this study than what could fit within a single paper. The idea for creating the special issue you are now reading was thus formed.

2 The Validation Benchmark

The lead paper in the special issue summarizes the FluidFlower forecasting study, which was the original vision for this body of work (Flemisch et al. 2023). That paper to a large extent summarizes the computational submissions of all participants and contrasts these to the actual results of the physical experiments, which for the sake of this study are defined as the ground truth.

The experiments are detailed in the second paper of this issue (Fernø et al. 2023). Here, details of the experimental design and conditions are given for five repetitions of the benchmark geometry. Moreover, significant additional data and analysis are provided, beyond what is used for the benchmark paper. This paper thus represents the most complete description of the data collected from the physical experiments.

Analysis of the experiments and the comparisons to computational results necessitated the development of new image analysis tools, especially tailored for images of transport phenomena in porous materials. These tools, and the open-source software used in the analysis of the experimental data, are detailed in Nordbotten et al. (2023).

3 Perspectives on the Benchmark Study

Two papers in this special issue provide broader perspectives on the benchmark study. The first of these considers the setting of the FluidFlower experiment from the perspective of classical scaling analysis and asks to what extent the processes observe scale faithfully to field conditions (Kovscek et al. 2024). This provides a broader context substantiating the relevance of the main study.

Secondly, Bauer et al. (2023) studied the question of how visual analysis can support the comparison of spatiotemporal ensemble data resulting from the FluidFlower experiment and simulations. Different data aggregation and interactive visualization approaches are explored. Concerning data aggregation, one key component is the choice of similarity metrics that define the relationship between different results. Regarding interactive visualization, dimensionality reduction methods are employed for overviewing the data and space–time cube volume rendering allows to investigate details.

4 Computational Insights and Learnings

Taking the original benchmark description as a starting point, several of the participating groups conducted in-depth analysis of various processes, uncertainty, and model fidelity. These topics, and general lessons learned, have been summarized in five contributions in this issue.

Wapperom et al. (2023) discuss the impact of various modeling choices on the outcomes of their simulation model, such as gridding and discretization methods. They additionally describe a custom nonlinear solver developed for the atmospheric benchmark conditions to improve convergence. Lessons learned are also discussed, emphasizing the difference to conditions commonly dealt with in subsurface simulation.

A computational framework for simulating of CO_2 storage in saline aquifers is presented in Wang et al. (2023) and validated by investigating the dynamics of gravity-induced convective transport. Applied to the FluidFlower benchmark scenario, the impact of hysteresis and the diffusion of CO_2 in liquid phase on the migration and trapping of the CO_2 plume are investigated.

Jammoul et al. (2023) presented an ensemble-based approach to quantify uncertainties in petrophysical properties and studies the predictability of numerical models. They highlight the importance of considering the uncertainties in the risk assessment of geological carbon storage projects.

An entire modeling workflow is described in Green et al. (2023), including the simplified model of the tracer tests and subsequent inversion of the permeability data, the open-source finite volume simulator, and the final numerical predictions and the reporting of key metrics—a study that allowed them mapping important uncertainties in the FluidFlower experiments.

Tian et al. (2024) conducted a comprehensive history matching study for the FluidFlower benchmark scenario. History matching is first performed based on a smaller-zoned structured model using a simple Poisson-like solver and then further enhanced by richer spatial and physical models to capture the spatial variation of permeability and buoyancy effects. The influence of the correspondingly calibrated parameters on the CO_2 concentration plume forecasts is thoroughly investigated.

5 Complementary Experimental Data and Analysis

The final four papers in this issue contribute additional studies related to the FluidFlower experimental rigs. These are of widely varying character and form a broader view on the possible applications of FluidFlower-type experiments.

The first paper in this section details the FluidFlower concept (Eikehaug et al. 2024). It contains the learnings from constructing not only the full-size FluidFlower used in the forecasting study, but also a family of smaller and more versatile experimental rigs.

The second paper in this section describes a family of experiments conducted in medium-sized FluidFlower rigs, of about 1 m by 0.6 m (Haugen et al. 2024). These experiments provide additional data across varying geometries, conceptually similar but materially different, to the geometry considered in the main study. Taken together, they allow for addressing what aspects of the study are generic, and what aspects are case-specific.

The questions of the value of local calibration data and transferability of the calibrated models to other settings are addressed in the third paper in this section (Saló-Salgado et al. 2023). The lead author visited Bergen and contributed to the medium-size FluidFlower experiments detailed in Haugen et al. (2024), but was not given access to the main FluidFlower forecasting experiment. This provided a context opportunity to evaluate the transferability of knowledge gained from calibration of models against the medium-size experiments to the experiments conducted on the large rig, thereby addressing the question as to whether such calibration data improves forecasting ability.

In the final paper of the special issue, the construction of a fully autonomous digital twin of a medium-size FluidFlower is reported Keilegavlen et al. (2023). This includes real-time data-analysis, ensemble forecasting computations, machine learning-based correction steps, and finally an optimal control of the wells in the experiment itself.

6 Summary

As a whole, we are very pleased to see the breadth of contributions to this issue and believe it contains a substantial contribution to the challenging topic of confronting computational modeling with real data.

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