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Differentiable Model for Muon Transport and Two-Phase Flow in Porous Media with applications to Subsurface Pollution Monitoring

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Various industrial processes in geological formations, such as carbon dioxide capture sequestration, underground energy storage, enhanced oil recovery, hydraulic fracturing, well disposal, etc. could present safety and environmental risks including groundwater contamination. In the case of storage, any leaks would also be detrimental for the performance of the capture system.

Non-aqueous phase liquids such as chlorinated hydrocarbons and oil, but also supercritical CO2 have low solubility in brine. Their migration, especially due to external forces, must be thoroughly monitored in order to avoid long-time pollution of freshwater aquifers in the subsurface.

In our investigation, we will focus on geological carbon storage (GCS). Detecting breakthroughs in the carprock as early as possible is crucial to prevent further pollution of subsurface layers and assess storage exploitation. Still, we will keep the discussion general enough as the models we implement apply beyond GCS to all of the situations mentioned above.

The use of atmospheric muons to monitor underground fluid saturation levels has been studied before. However, the low-contrast and possibly noisy muon flux measurements require accurate and realistic modeling of the main physical processes for the inverse problem behind monitoring. Moreover, first order sensitivity information for control parameters is needed to improve the analysis.

We address those issues in present work by incorporating a differentiable programming paradigm into the implementation of the detailed physics simulations in our set-up. The exposition is

organised in the following manner. Firstly, we describe a model for the two-phase flow with capillary barrier effect in heterogeneous porous media for which we rely on the mixed-hybrid finite element method (MHFEM). Compared to previous studies, we develop a full 3D simulation and provide details for the implementation of adjoint sensitivity methods in the context of MHFEM. Secondly, we discuss muon transport building upon the Backward Monte-Carlo (BMC) scheme from V. Niess et al. (Comput. Phys. Comm. 2018). We re-use the spatial discretisation from MHFEM and perform sensitivity computations with respect to the media density and saturation levels following R. Grinis (arXiv:2108.10245 accepted to JETP 2021). Finally, we put everything together to design a system for detecting CO2 leakage through the caprock layer in GCS sites.