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A Vision Transformer for Size-Agnostic Modelling of Two-Phase Drainage in Complex Porous Media Considering Wettability, Interfacial Tension, and Resolution

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The estimation of pore-scale multiphase flow fields in complex geometries using deep learning has proven challenging. This is partly because researchers have historically focused on model architecture and data quality, while the volume and variety of data may have been inadequate to capture the intricacies of multiphase flow. In this work, we introduce a novel deep learning methodology to predict phase distributions within realistic porous rocks during two-phase capillary-dominated drainage. We use Computerised Tomography (CT) images and incorporate pressure gradient, resolution, wettability (contact angle), and interfacial tension as inputs without relying on complicated expert-crafted features.

To create ground-truth datasets, we extract subsamples from CT scans of both synthetic and real rocks, including sandstones and carbonates. Primary drainage is then simulated in these sub-images by an in-house Pore Morphology-based Simulator (PMS), yielding millions of fluid occupancy instances. To maintain both pixel-wise accuracy and physical fluid connectivity, we devise a Higher-Dimensional Vision Transformer (HD-ViT). We train the model on phase distributions where the wetting phase is drained from pores solely based on their sizes, regardless of their relation to other pores and the inlet, allowing the network to focus on subtle details such as generating valid fluid-fluid interfaces. Fluid continuity is then enforced as a post-processing step by removing patches of the invading phase that are not connected to any desired inlet(s). This approach facilitates efficient inference for images of varying sizes and resolutions with any inlet-outlet setup. After training on a massive dataset of images and rock-fluid data, the model achieves outstanding results with a testing F1 score and saturation correlation coefficient above 0.95.

We confirm the model's validity by demonstrating consistently high performance on larger images of unseen sandstone and carbonate rocks through an effective patch-and-stitch strategy. The model maintains accuracy across a wide range of scales, from microns to centimetres, within the range of properties used in this study. Such scalability enables distributed computing, facilitating the processing of extremely large images. Therefore, the reported methodology can be considered a solution to the computational constraints encountered for large images. Interestingly, the HD-ViT proves even faster than the PMS, itself considered one of the most efficient simulators of drainage. This underlines the immense potential of models trained at scale, like ours, to be fine-tuned for computationally intensive simulations using smaller datasets, where the speed advantage becomes increasingly significant.

Our final model introduces multiple innovative aspects. Firstly, setting it apart from similar models, ours incorporates all factors influencing capillary drainage as inputs, offering a comprehensive approach. Secondly, the model is trained on a dataset of unprecedented size and diversity, comprising millions of highly heterogeneous and realistic images. Thirdly, by avoiding complex feature engineering, we ensure an end-to-end, easy-to-use model. Fourthly, we implement a simple and effective strategy to enforce phase connectivity in fluid distributions and to also allow for size-agnostic predictions on any inlet-outlet configuration. As such, the HD-ViT is a multiscale, practical, and efficient model for pore-scale drainage.

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