A multi-class approach for the pore-scale flow in unconventional reservoirs

Introduction

Digital rock analysis (DRA) has proven to be useful for the prediction of petrophysical properties of conventional reservoirs, where the pore space is captured well by modern μCT scanners with a resolution of 1-5 μm (Saxena et al. 2015). The situation changes drastically for unconventional reservoirs. They are characterized by small pores that are poorly resolved (if at all) by a μCT scanner. This underestimation of the pore space has a crucial impact on permeability computation and yields a wrong estimation of the reservoir productivity. Hence sophisticated methods are required to take into account the unresolved pore space (Soulaïne et al. 2016, Abu-Al-Saud et al. 2020).

We suggest a following workflow to include unresolved pore space in the pore-scale flow modelling: (a) high-contrast μCT imaging technique to identify the unresolved porosity and create a multi-class digital rock model, (b) FIB-SEM and Stokes flow solver to create a micro-porosity – permeability correlation and assign permeability to each voxel of the multi-class model, and (c) Stokes-Brinkman flow solver to finally compute the absolute permeability of the multi-class model of the rock sample. The novelty of our workflow is the application of high-contrast imaging, which detects and quantifies the unresolved pores, resulting in a significantly better modelling quality. We successfully apply this workflow to a low-permeable rock sample of Achimov deposits. The computed permeability compares well to the experimental value.

Methodology

In general, the workflow to compute the absolute permeability of a rock sample consists of the following steps: (a) an image acquisition, (b) an image filtering, (c) an image segmentation, and (d) a single-phase flow simulation, see Figure 1.

![Workflow Image](image-url)

**Figure 1.** A typical workflow to compute the absolute permeability of a rock sample.

In the first step, two μCT scans of a rock sample of Achimov deposits are made with a resolution of 3 μm. The first scan of a dry (air-saturated) sample is used to identify big, well-resolved pores. The second scan of the sample, saturated with xenon, is used to detect unresolved pores. Xenon is a contrast media that even in small amounts actively absorbs X-rays (Mayo 2015). Therefore, applying xenon increases the contrast between solid rock and unresolved porous regions. Comparison of a dry sample and xenon-saturated sample yields the unresolved pore regions.

Before the image segmentation, all μCT scans are filtered with a bandpass and a bilateral filter to reduce the noise and CT artifacts. According to our experience, this filter combination is easy to use and yields appropriate results in a short time (Diwakar and Kumar 2018, Orlov et al. 2021), see Figure 2.

The dry sample is segmented by means of a Random Walker algorithm (Grady 2006, Orlov et al. 2021). The segmentation is briefly explained in Figure 3. Two global thresholds are introduced manually so that they identify clearly the pores (lower threshold) and the grains (upper threshold). The labelling in the undefined (grey) zone is provided by the Random Walker.
Figure 2. An original μCT scan (left) and a filtered scan (right).

The unresolved pore regions, extracted from the xenon-saturated scans, are shown in Figure 4 (left). Figure 4 (right) shows the corresponding intensity histogram of the unresolved pore regions. We assume a linear relationship between the intensity $I$ and the unresolved porosity $\phi_{\text{micro}} = a \cdot I + b$ and assign a micro-porosity value (from 0 to 100%) to each voxel creating a multi-class micro-porosity model.

Now we need to create a multi-class permeability model, i.e. assign a permeability value to each voxel with the unresolved porosity. For that reason, we take several micro-samples from the rock sample and apply Focussed Ion Beam milling combined with Scanning Electron Microscopy (FIB-SEM) to create 3D micro-models with a resolution of 15-35 nm (Kelly et al. 2016). These models show the real structure of the micro-porosity (see Figure 5) and hence can be used to build a correlation between micro-porosity and absolute permeability. We run Stokes simulations for these micro-models to fit permeability $K_{\text{micro}}$ as an exponential function of micro-porosity $\phi_{\text{micro}}$: $K_{\text{micro}} = 7.251 \cdot 10^{-5} e^{0.147\phi_{\text{micro}}}$ (mD), see Figure 6. This correlation function is used to create the desired multi-class permeability model.

Finally, the Stokes-Brinkman flow-solver is applied to the multi-class permeability model to compute the absolute permeability of the sample. The Stokes-Brinkman solver accounts for flow through the pore space and semi-permeable media with a given permeability (Iliev et al. 2013).

Results

The permeability of this sample, measured experimentally with hexane, is 0.033 mD. The digital rock model has a resolution of 900³ voxels (2.7³ mm³). The model without unresolved pore regions has a porosity of 7.8% but shows no connectivity, so it is impermeable. Inclusion of the micro-porosity
connects the well-resolved pores, increases the overall porosity to 11.1%, and yields a permeability of 0.059 mD, which has the same order of magnitude as the experimentally measured value.

**Figure 4.** Left: a slice of the 3D model with well-resolved pores (black) and unresolved porous regions (grayscale). Right: a corresponding intensity histogram of the unresolved pore regions.

**Figure 5.** The FIB-SEM approach: a SEM image (left), FIB-SEM images (middle), a 3D pore-space model (right).

**Figure 6.** The micro-porosity – permeability correlation computed for micromodels (FIB-SEM), samples are shown by blue circles, a blue dotted line is a fitted exponential curve.
Conclusions

The pore-scale modeling quality of unconventional reservoirs has poor quality due to small pore sizes that cannot be detected by standard μCT scanning techniques. The combination of high-contrast μCT imaging, FIB-SEM and Stokes-Brinkman flow solver allows to include the unresolved pore space in the permeability computation, thereby significantly increasing the model accuracy. This novel approach performs well on a low-permeable rock sample of Achimov deposits.

Future studies should perform a deep sensitivity analysis to identify the most critical points in the proposed approach. Finally, the multi-class approach should be extended to multiphase flow, enabling computation of relative permeability curves for unconventional reservoirs. Both above-mentioned topics are in the scope of our current research.

References


