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# Understanding pre-Darcy flow and velocity-dependent permeability in porous rocks through neutron imaging

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Darcy's Law is a classic example of a scientific paradigm in the study of fluid migration through porous media. However, many authors have reported deviation of flow regimes from Darcy's law at low flow velocity [1] when analyzing fluid flow in rocks, often called pre-Darcy flow. In addition to the velocity dependence of rock permeability, the heterogeneous nature of geomaterials deserves equal attention when analyzing the hydraulic behavior of rock masses. When performing conventional permeability tests, little is known regarding fluid behavior within the sample. In this context, neutron imaging provides an ideal full-field technique for better understanding these phenomena. This work employs neutron imaging to investigate the influence of sample heterogeneity and flow rate on flow paths and permeability by performing flow tests with Idaho Gray sandstone cores.
In-situ experiments were performed at the Neutra instrument at Paul Scherrer Institut (Switzerland) using the setup described in Vieira Lima et al. [2]. The flow tests were carried out on samples saturated with heavy water (D2O) or normal water (H2O) by pressure-driven percolation of the respective opposite fluid. Before the neutron experiments, x-ray tomograms were acquired to provide a reconstructed 3D image with a cubic voxel width of 13 µm for a detailed characterization of the pore and grain structures. During each test, neutron radiographies were acquired with an exposure time of 1 s, generating 2D images with a 200 µm pixel size. The difference in neutron attenuation between D2O and H2O was exploited to track the advance of the infiltration front; as D2O and H2O are otherwise very similar fluids, a near single-phase fluid condition was assumed. Boundary fluid flow-rate and pressure measurements were recorded and correlated with the images.
The raw neutron images were processed using in-house python codes, generating maps of saturation-time and -degree plus flow-speed fields. 3D porosity fields and pore network models (using Porespy software [3]) were generated from the x-ray tomograms. Simulations of the visualized phenomena were performed using the "Invasion Percolation"and the "Stokes Flow"algorithms from the OpenPNM package [4] based on the 3D pore networks.
Pre-Darcy flow was observed from the boundary measurments in all samples (Fig.1) with a reduction in the bulk permeability with the flow rate. The results from the neutron radiography in the form of 2D maps of the flow-field evolution showed that the percolation followed preferential paths due to the natural heterogeneity of the samples (Fig.2), which could be correlated with the heterogeneity in the porosity fields (Fig.3). In the injection of either of the percolating fluids (H2O and D2O), the flow rate increase generated a flattening of the advancing flow fronts and reduced spatial heterogeneity of the infiltration, indicating that more pores were accessed at higher injection rates and suggesting threshold rates/pressures exist to access different parts of the pore network. The simulations of the fluid infiltration using the pore network models reproduced well the observed flow patterns and showed a good performance in predicting the change in bulk permeability for each flow rate.

## Participation

In-Person

## References

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