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3D X-ray micro-velocimetry of unsteady multiphase flows in porous media

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Multiphase flow in porous media is an important process in a variety of Earth science applications, from groundwater remediation to subsurface CO2 and H2 storage. The associated pore-scale flow dynamics have been the subject of active research for decades, due to their non-linear nature and the difficulty of measuring and modeling them in the complex pore geometries of geo-materials. While progress in X-ray micro-computed tomography (micro-CT) has enabled to investigate the morphology of fluid distributions and menisci (Singh et al. 2019), measurements of the underlying flow dynamics (i.e. flow velocity fields) have remained impossible. This is because state-of-the-art micro-velocimetry techniques either require optically transparent porous samples with index-matched fluids, or do not currently provide the necessary spatial and temporal resolutions.

In this work, we present a breakthrough in 3D X-ray particle tracking velocimetry applied to capillary-dominated drainage in porous sintered glass and Ketton limestone samples. The method builds further on our lab-based X-ray velocimetry method (Bultreys et al. 2021), extending it to synchrotron micro-CT at the TOMCAT beamline of the Swiss Light Source. Time resolved tomography at 250 ms per tomogram and 2.75 µm voxel size was used to track µm-scale tracer particles in the non-wetting phase while it was injected into the pore space at a constant low flow rate. Our results showed that Haines jumps caused fluctuations in the flow field of the non-wetting phase, with local velocities exceeding the interstitial (injection) flow rate by up to two orders of magnitude. In accordance with previous studies based on, e.g., pressure measurements, the main fluid displacement during Haines jumps took place on the order of 1 to a few seconds. Subsequently, the resulting velocity fluctuations decayed over tens of seconds. Contrary to prior studies, our results also give insight into the spatial structure of the fluctuations. The velocity fluctuations originating from Haines jumps propagated through the porous medium as rolling waves with speeds on the order of mm/s - much slower than the speed of pressure waves (i.e., the speed of sound in the non-wetting phase, ~km/s) –accompanied by retraction of fluid menisci in locations away from the main Haines jump. Such velocity waves reached long distances into the porous medium, with decay lengths exceeding 30 times the characteristic pore size, where the velocity magnitude was still an order of magnitude higher than the injection rate. This indicates the possibility for long-range non-local effects due to capillary instabilities during drainage. Successive Haines jumps reactivated flow paths in the same regions, which appeared to have similar decay times.

The results presented here are the first pore-scale velocimetry measurements of (unsteady) multiphase flow in rocks and possibly in any 3D porous material. The study sheds light on the spatial and temporal structure of capillary fluctuations in 3D porous media, which are of central importance in newly emerging upscaling theories for multiphase flow (McClure et al. 2021).

Participation

In-Person

References

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