4D X-ray velocimetry of multiphase flows in porous media

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Many natural and industrial processes depend on fluids displacing each other in porous materials. However, multiphase flow dynamics in porous media are still poorly understood due to the complex interplay between capillary, viscous and inertial forces. Research on this topic has been hampered by the lack of methods to measure flow fields in optically opaque, microscopic 3D geometries : while X-ray micro-computed tomography (micro-CT) has enabled the visualization of fluid distributions and menisci in the pores, measurements of the underlying flow dynamics (i.e. velocity fields) have so far remained impossible. In this work, we introduce a novel 4D micro-velocimetry method based on synchrotron micro-CT with fast imaging rates (up to 4 Hz at 2.75 μm voxel size) at the TOMCAT beamline of the Swiss Light Source. This was used to perform Lagrangian particle tracking of μm-scale tracer particles in the flow through the pores of natural rock and filter samples. The measurements resulted in time-resolved and fully three-dimensional (3-component) flow fields during unsteady-state drainage, where oil displaces water from the pores at slow, constant injection rates. The data enabled to calculate how fluid displacements convert interfacial energy into kinetic energy, corresponding to velocity perturbations in the pore-scale flow field. Our analysis suggests that these perturbations are long-ranged, impacting the pore-scale viscous-capillary force balance and the representative volume needed for averaging. Furthermore, the perturbations enhance solute and colloid transport in unsaturated porous media. Overall, we show that 4D X-ray velocimetry opens new pathways to investigate flow in porous materials, relevant to e.g. groundwater pollution remediation and subsurface storage of CO_2 and hydrogen.

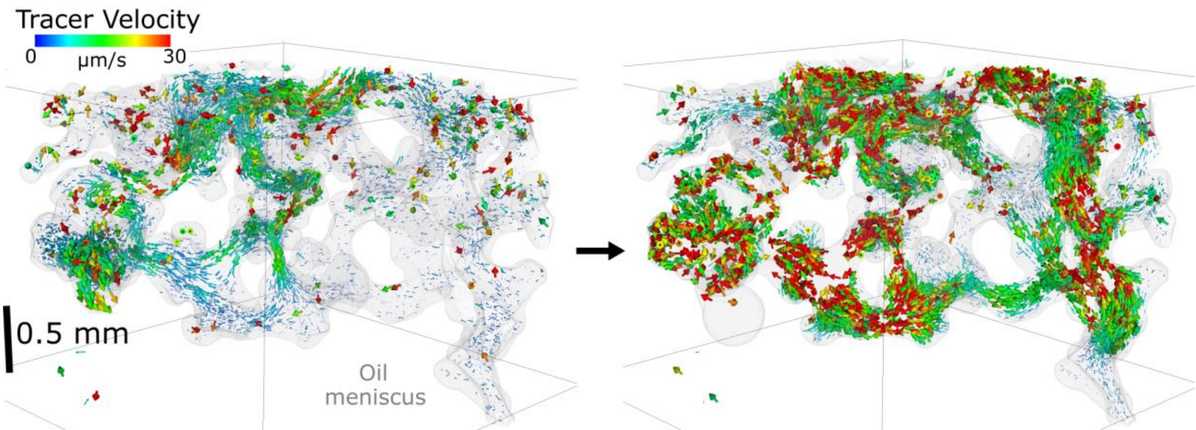

Figure: 4D particle tracking of micrometer-scale flow tracers in the non-wetting phase (oil) during a drainage experiment on a porous filter sample. The two stills are from tomograms 1.25 s apart ; each with an acquisition time of 0.25 seconds and a voxel size of 2.75 μm. The grey transparent surface shows the oil meniscus in the pores. Oil invades pores in sudden movements called Haines jumps, triggering acceleration in the 3D flow field related to oil redistribution in the surrounding pores. This flow field perturbation extends throughout nearly the entire sample and results in remarkably tortuous flow paths.

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