Fluid rearrangements during Haine's jumps using time-resolved micro-computed tomography

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Multiphase flow in porous media has high societal relevance, for example in geological CO_2 sequestration and gas diffusion in fuel cells. Intensive research over several decades has been conducted on multi-phase flow in two dimensions using setups such as Hele-Shaw cells[1,2]. Advances in X-ray sources and detectors have made time-resolved studies of flow in three-dimensional porous media feasible through computed tomography (CT). Time-resolved CT is usually carried out at synchrotron facilities, because home-laboratory setups have a low photon flux resulting in long exposure times and consequently poor time resolutions. However, by utilizing advanced tomographic reconstruction algorithms exploiting *a priori* information about the sample, one can alleviate the projection sampling requirement, reducing the time-resolution down to tens of seconds, compared to minutes or hours in the case of regular CT scans[3].

Here, we present results from a time-resolved two-phase flow imbibition and drainage experiment using an industrial CT instrument (Nikon) with a custom-made sample stage, giving a spatial resolution better than 10 μm and a time resolution of about 30 s per scan [4][Tekseth *et al.,* to be published]. The porous sample was a sintered glass bead pack of 250-500 μm diameter soda-lime spheres initially filled with a (non-wetting) air phase in a capillary of 2.5 mm inner diameter. The dynamics consisted of first injecting and then withdrawing a 0.5 M KI doped water at a volumetric flow rate of 0.12 μL/min. The good time-resolution was achieved by acquiring undersampled tomographic datasets and using an iterative algorithm that utilizes both *a priori* sample information and *compressed sensing* techniques to faithfully reconstruct the 3D sample[5]. Specifically, the algorithm exploits that the sintered and inert glass beads were stationary throughout the experiment. The acquisition time was further reduced by placing the syringe pumps on a rotational stage with power being transferred through a slip ring, allowing repeated rotations in one direction (see Fig. 1A).

The results showed a stable displacement process of air by doped water during imbibition, while the drainage process was dominated by fingering, consistent with literature[6,7]. During drainage, we observed slow interfacial fluid curvature changes followed by quick pore-filling events (cf. Fig 1D), consistent with what is known as Haine's jumps[8]. Preliminary results also indicate that these Haine's jumps, with a volume of about 0.05 μL, can be reversible and repeated, by cycling the volumetric flow rate periodically [4][Tekseth *et al.,* to be published].

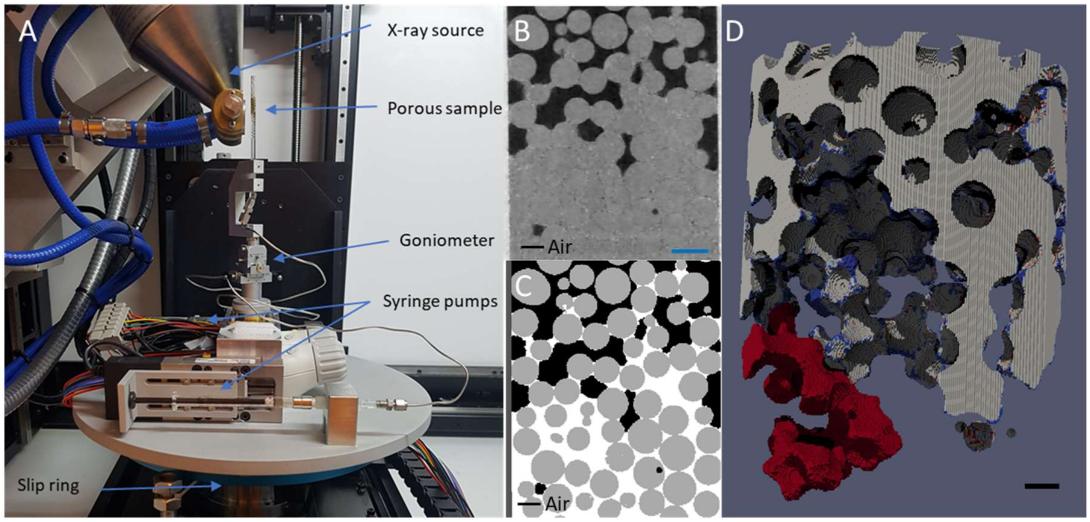

Figure 1: A) Experimental setup with the syringe pumps and fluid supply lines on the rotational stage, allowing continuous rotation in one direction. B) Reconstructed, and C) segmented cross-section of the sample at one timestep during drainage when the water is pulled back and being replaced by air. D) 3D rendering of C) showing the air phase in several colors. Gray regions indicate pores stationarily filled with air, blue regions denote air replaced by water, and red regions are newly air-filled pores, from one timestep to the next, highlighting the fluid rearrangements that take place during the Haine's jump. Scalebar: 250 µm.

The combination of the experimental setup and the reconstruction algorithm presented here has the potential to explore a wide range of 3D multi-phase flow phenomena in porous media, in the home-laboratory for challenging and calibrating theoretical models.

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