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Investigating Pore-scale air-water interfacial fluctuations in multiphase flow via time-resolved X-ray computed tomography

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Multiphase flow in a porous media is a widespread phenomenon with significance spanning from daily life to cutting-edge scientific fields and has hence been studied for centuries. Notable examples in geophysics include environmental cleanup, CO2 sequestration, and water purification. When one fluid phase displaces another inside a porous medium, intricate dynamics plays out across diverse spatial and temporal scales. In the case of multiphase flow, properties like relative permeability are estimated at the macroscopic "Darcy"level without accounting for the millisecond time-scale pore events. Despite progress, real-time imaging of fast (millisecond) events happening at the pore scale in 3D has historically been difficult. In this study, we showcase a method to consistently replicate and visualize pore-scale dynamics during drainage and imbibition. Using advanced X-ray computed tomography (CT), we achieve 4D imaging at the natural timescale of these events. Our approach relies on hydraulic pumping and a high-speed X-ray imaging system, recording 2,000 frames per second to deliver a temporal resolution of 0.5 milliseconds. This technique has enabled us to track the real-time movement of fluid interfaces. For example, we obtain a precise, quantitative visualization of rapid pore-filling events known as Haines jumps, rather than just snapshots taken before and after the events. We will also discuss how fast pore-scale processes are influenced by varying flow rates and capillary numbers during drainage. These findings illuminate the underlying physics of multiphase flow and demonstrate the promise of our imaging technique for future investigations in areas such as geoscience, biomedical engineering, and beyond.

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