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Synchrotron 4-dimensional imaging of two-phase flow through porous media

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ABSTRACT

Near real-time visualization of complex two-phase flow in a porous medium was demonstrated with dynamic 4-dimensional (4D) (3D + time) imaging at the 2-BM beam line of the Advanced Photon Source (APS) at Argonne National Laboratory. Advancing fluid fronts through tortuous flow paths and their interactions with sand grains were clearly captured, and formations of air bubbles and capillary bridges were visualized. The intense X-ray photon flux of the synchrotron facility made 4D imaging possible, capturing the dynamic evolution of both solid and fluid phases. Computed Tomography (CT) scans were collected every 12 s with a pixel size of 3.25 μm. The experiment was carried out to improve understanding of the physics associated with two-phase flow. The results provide a source of validation data for numerical simulation codes such as Lattice-Boltzmann, which are used to model multi-phase flow through porous media.

INTRODUCTION

Geometrical characterization of porous media provides crucial information for predictions of fluid flow/transport as well as structural/mechanical properties. The geometry influences not only a single fluid phase transport property such as permeability, but also multi-phase flow properties. Multi-phase flow is of great interest for applications such as enhanced oil recovery. X-ray Computed Tomography (XCT) allows non-destructive characterization of geometrical properties in 3D. Predictions of single and multi-phase flow parameters have been carried out based on geometrical information obtained from XCT[1]. Multi-phase flow through porous media, however, is a complex and dynamic problem with a lack of experimental data to validate modeling results. Some previous approaches included the use of neutron imaging to take advantage of high neutron contrast to water[2, 3]. The information is often limited to two-dimensions for dynamic radiography, and the dynamic information is lost in 3D CT scans due to long acquisition time. A similar limitation exists with a typical medical or laboratory XCT system[4]. A high-resolution CT scan can now be acquired within a few seconds or less allowing multiple CT scans to capture dynamic events, due to high flux of a synchrotron source, high camera speed, and application of a fast phase retrieval algorithm[5, 6]. A similar development was also made with a laboratory system recently[7]. In this paper, the authors successfully performed a 4D imaging of two-phase flow through porous media at a synchrotron imaging beam line, and interesting preliminary results are presented.

EXPERIMENT

A two-phase flow imbibition experiment was carried out at the 2-BM beam line of the Advanced Photon Source (APS) at Argonne National Laboratory, USA. An experimental setup was designed to allow continuous rotations of a flow chamber and avoid hose and electrical wire entanglements. A small piezoelectric pump assembly reduced the overall size and weight of the setup, which enabled the entire setup to be placed above a rotary stage (Figure 1). Flow rate could be adjusted by using a needle valve, and a flow rate of approximately 0.0755 µl/s was used. A slip-ring device provided electrical contact through the rotary stage for powering and controlling the pump assembly. A small amount of contrast agent (3 % KI) was added to distilled water. A densely packed (100 % relative density) Ottawa sand (0.425 mm to 0.85 mm in diameter) column was used.

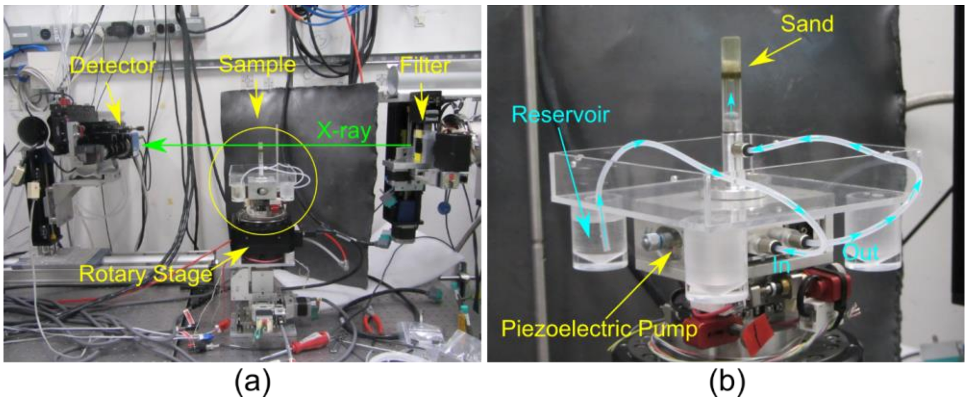

Figure 1: Experimental setup at APS 2-BM (a) and fluid flow experimental setup (b)

A pink beam spectrum (peak: ≈ 27 keV) with glass filters (3 mm) and a detector setup with a complementary metal-oxide semiconductor (CMOS) camera and a scintillator (25 µm-thick LuAG:Ce) were used. An effective image pixel size of 3.25 µm was achieved with an optical magnification (x2) of the lens. Out of the available 2560 × 2160 pixels of the CMOS sensor, 2560 × 1200 pixels were used due to the limited pink beam height, achieving a field of view (FOV) of 8.3 mm × 3.9 mm. During the continuous rotation of the rotary stage (4320^o total), images were collected at a fixed increment (50 Hz). As a result, 600 images were obtained for 12 s during 180^o rotation with an exposure time of 2 ms per image. A distance of 400 mm between the sample and the detector was allowed for the phase retrieval process.

RESULTS AND DISCUSSION

Due to poor exposure conditions (2 ms) during the dynamic imaging, attenuation based reconstruction did not provide high enough contrast. A phase retrieval algorithm significantly improved image contrast using a CT reconstruction software (TomoPy) (Figure 2)[8, 9], publicly available at APS. Darter, a high-performance computing system at the National Institute of Computational Science (NICS), was used for CT reconstruction. A time-lapsed CT sequence provides uninterrupted dynamic fluid flow information (Figure 3). Selected cross-sectional CT slices at the same location are shown. Minimal blur is expected at the flow front as the fluid injection rate is substantially smaller compared to the CT acquisition rate. Clear spherical shapes of air bubbles show that the features were not changing significantly compared to the CT acquisition rate. The pore structure was initially dry at 6 s, but some fluid infiltration was visible at 30 s after fluid flow was initiated. Tiny air bubble formations were noticed at 102 s, and these bubbles appear to have grown larger at 150 s. At 150 s, a majority of the pore space was filled with fluid except for some air bubbles. These bubbles appear to have migrated and coalesced with each other, ultimately forming capillary bridges, as shown in the CT images at 246 s or 270 s. This finding provides a valuable experimental observation of fluid flow behavior in the capillary fingering regime. Figure 4 provides 3D information of sand grains shapes and geometric orientations as well as the fluid flow evolution from 30 s to 102 s. Formation of air bubbles is also visible at the bottom of the volume from slices B-B and C-C Thin films of fluid around sand grains are also observed from visualizations in the three directions.

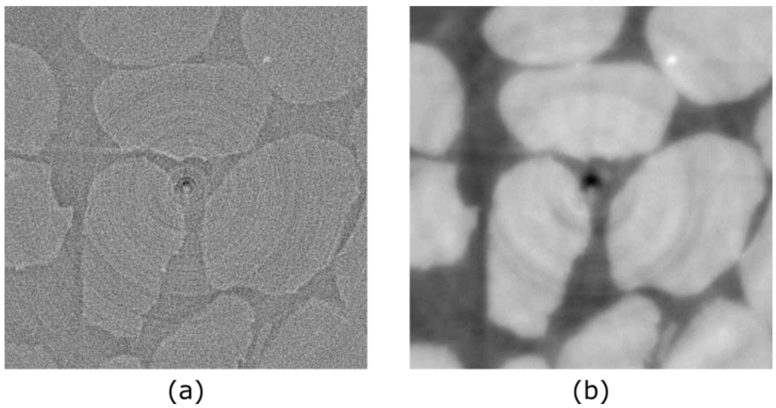

Figure 2: Reconstruction results using attenuation only (a) and phase retrieval (b)

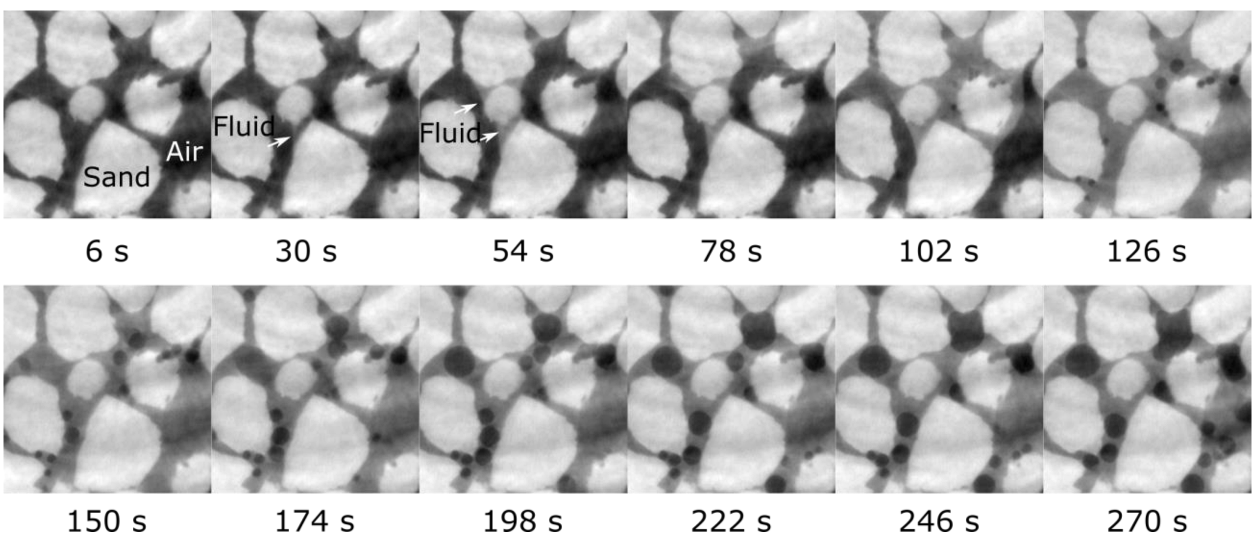

Figure 3: Time-lapsed CT images

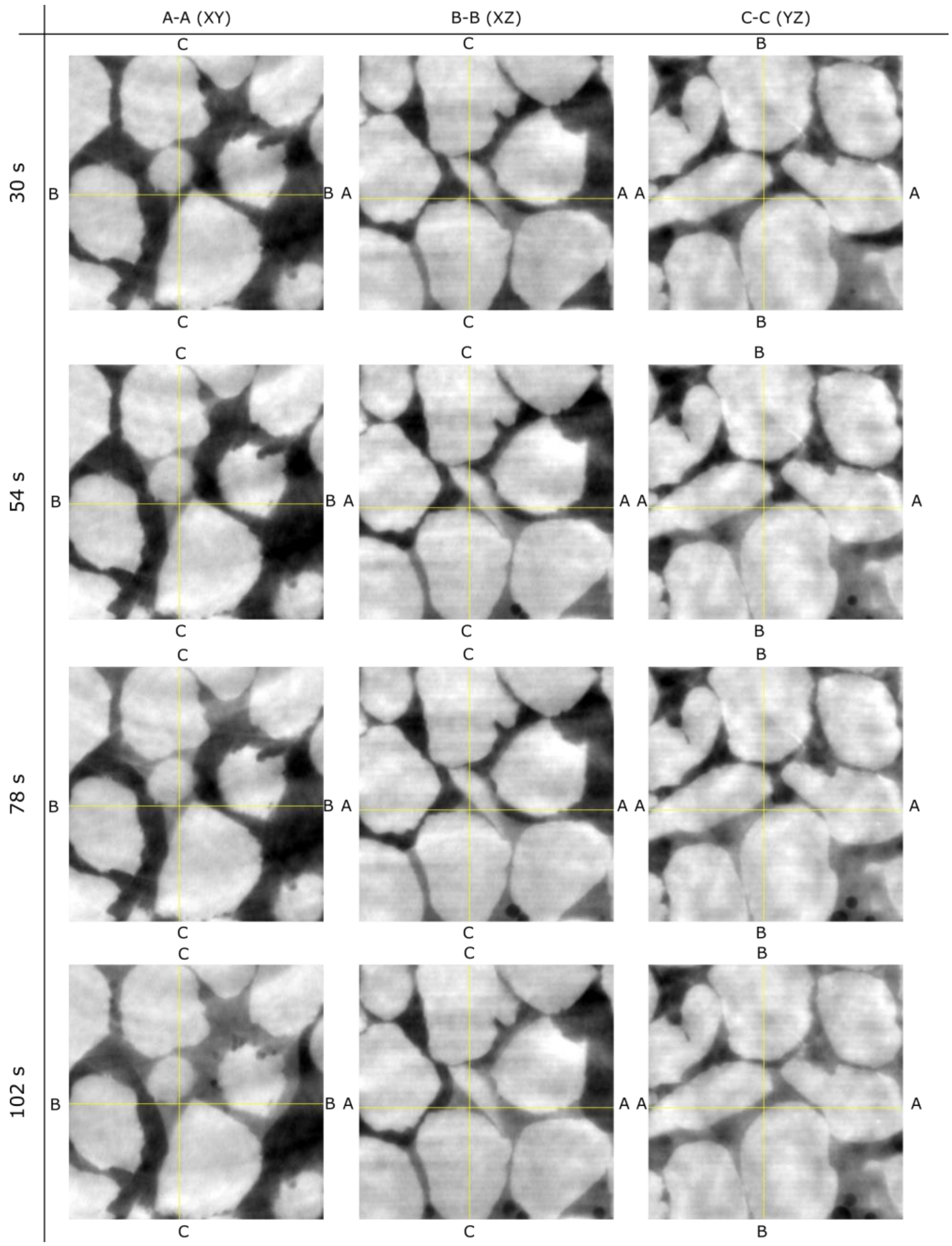

Figure 4: Time-lapsed CT images at orthogonal orientations

Quantitative analysis requires some image processing and image segmentation steps. Further improvement of the CT images using iterative reconstruction algorithms will be explored along with different ways to segment the three main phases (sand, air, and fluid).

CONCLUSIONS

An in situ two-phase flow imbibition experiment was successfully carried out at a synchrotron imaging facility. High-resolution dynamic 4D imaging of fluid flow through porous media revealed complex fluid imbibition processes in the capillary fingering regime. Almost real-time information is achieved from continuous 12 s CT acquisition time. Interesting bubble formations and coalescences of the bubbles leading to capillary bridge formation were discovered. The authors are also working on a project related to detecting and characterizing defects occurring in metal parts produced with Additive Manufacturing using XCT, including during in-situ loading. Determination of the probability of detection of critical defects using XCT will be explored, which is an ongoing research project.

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