Using X-ray Microtomography to Determine Gas and Liquid Phase Distributions in Porous Media

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Introduction

A common problem in understanding unsaturated flow processes is the lack of information about the porous medium and the processes governing flow and transport at the pore scale in a porous material. In recent years, there has been an increased interest in issues such as network modeling,[1] Lattice-Boltzmann modeling (e.g., [2]), dynamic vs. steady-state or static flow processes (e.g.,[3,4]) from researchers in soil science, water resources, and the petroleum industry.

In previous work by the authors it has become evident that the methods we use to measure the hydraulic properties can have a significant impact on the obtained results. In particular, a dependence on drainage flow rate has been observed, suggesting interference from dynamic phenomena such as air entrapment, pore-water blockage, influence of flow velocity on the solid/liquid-gas contact angle, etc. Generally, more water is retained at a given capillary pressure for dynamic drainage than for static equilibrium and steady-state cases.[3,4,5,6] As many researchers now use new faster methods to determine the hydraulic characteristics of porous materials, it is important to examine the influence of the boundary conditions on the measurement results for these experiments.

An argument can also be made that a fundamental understanding of flow and transport mechanisms in porous media can be achieved only by studying pore-scale processes. These mechanisms operating at the microscale cannot be measured with traditional techniques, which generally require insertion of a sensor at or near the region of interest. X-ray computed microtomography (CMT) overcomes this problem via the noninvasive observation of changing fluid-phase content and solution concentration.

Methods and Materials

CMT is a technique for determining the internal structure of an object. It uses projection views (radiographs) from different angles to mathematically reconstruct the complete three-dimensional image of the object. The physical basis for the technique is the absorption or attenuation of the penetrating electromagnetic radiation by the object. The attenuation depends on the density and the atomic constituents of the material that is scanned, and the transmitted radiation is compared to the incident radiation to reconstruct a map of attenuation coefficients versus position in the object.

By adding a dopant (KI) to the fluid phase and scanning at the peak absorption energy for iodide, we achieved sufficient contrast between air and fluid phases and could thereby resolve the distribution of the phases as a function of varying flow conditions. Using the GeoSoilEnviroCARS (Advanced Photon Source sector 13) CMT instrument, we scanned cylindrical samples of sand packs (6 mm and 1.5 mm inside diameter) during drainage. Two types of experiments were performed on the samples: (1) one-step experiments in which drainage was induced with one relatively high air-phase pressure and (2) multi-step experiments in which a varying number of smaller pressure increments were applied. Spatial and temporal changes in water saturation could then be compared for cases in which different fluid flow rates apply.

Results

Examples of the images obtained are illustrated in Figs. 1a and 1b. The figures show two horizontal slices through the center of a 6-mm-diameter packed-sand core in the identical position, but scanned after two different types of experiments were performed on the sample. A Lincoln fine sand with a mean particle size of 0.17 mm is shown in all images. Figure 1a illustrates conditions after the core has been drained slowly to a final capillary pressure of 490 cm using a multi-step approach, whereas Fig. 1b

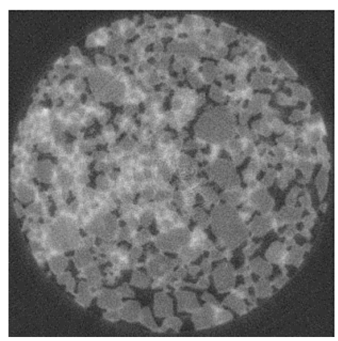

FIG. 1a. CMT image of horizontal slice through a 6-mm-diameter sand-pack, drained at a low flow rate to a final capillary pressure of 490 cm.

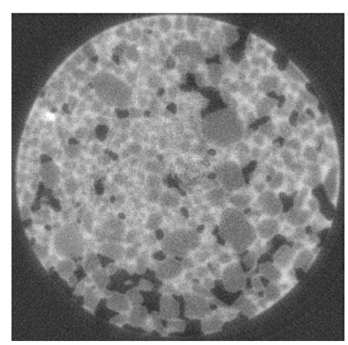

FIG. 1b. CMT image of horizontal slice through a 6-mm-diameter sand-pack, drained at a high flow rate to a final capillary pressure of 490 cm.

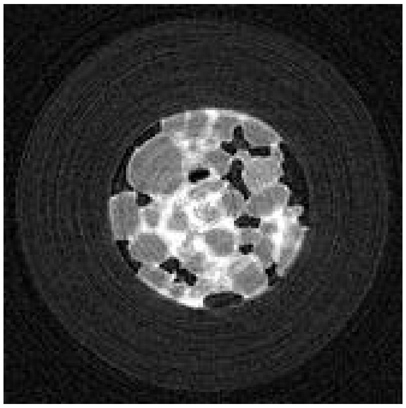

FIG. 2. CMTimage of hor - izontal slice through a 1.5-mm-diameter sand-pack. Individual pores and water menisci can be detected.

is a scan performed after the core has been drained very quickly using just one large pressure step of 490 cm. In the images, white represents water, black is air, and gray is the solid phase. Image resolution is defined by a pixel size of 17 µm. Clearly, there are major differences in overall amount of water retained in the sample, but the distribution is also very different. For the fast drainage scenario, most of the water has preferentially drained off in a few larger pores, and the bulk of the matrix is still saturated, whereas the slow drainage results in a much more uniform drainage of the sample. For the material investigated in this study, microtomography has proven to be an extremely useful tool for tracking changes in fluid saturation, but even finer details of the flow process can be observed in Fig. 2, which is a slice through a 1.5-mm sand-pack of the same sand. For a sample this size, the obtained resolution is based on a pixel size of approximately 7 µm. In this case, individual pores and the fluid meniscus curvature can be detected.

Discussion

X-ray CMT offers the possibility for noninvasive investigations of dynamic flow and transport processes on the pore scale and the opportunity to quantitatively explain the observed flow-rate-dependent phenomena. Moreover, we expect that the high-spatial resolution measurements will provide a unique database that can be used for verification of Lattice-Boltzmann simulations or network modeling of flow and transport in unsaturated porous media.

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