Quantifying Pore-scale Flow Processes with X-ray Microtomography

D. Wildenschild,[1] B. S .B. Christensen,[1] J. W. Hopmans,[2] A. J. R. Kent,[3] M. L. Rivers[4]
[1]Environment & Resources, Technical University of Denmark, Lyngby, Denmark
[2]Hydrologic Science, University of California, Davis, CA, U.S.A.
[3]Danish Lithosphere Centre, Copenhagen, Denmark
[4]Consortium for Advanced Radiation Sources (CARS), The University of Chicago, Chicago, IL, U.S.A.

Introduction

Pore-scale fluid distributions and their variation in time and space dictate continuum-scale properties, such as capillary-pressure relationships and relative permeability properties, which again control multiphase flow and contaminant transport in porous media. We need to make pore-scale or microscale measurements and achieve a basic comprehension of these processes to improve our understanding of these findings and subsequently upscale them to field scale. Thus, 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 contents and solution concentrations.

In the past three years, we have performed x-ray microtomographic work at the GeoSoilEnviro Consortium for Advanced Radiation Sources (GSECARS) sector at the APS to investigate the flow of fluid and gas phases in porous media under various experimental conditions to enhance our understanding of how these processes act at the pore scale. Some of the challenges that motivate us are to (1) investigate differences between static and dynamic flow phenomena; (2) quantify and therefore better understand the influence of interfacial properties, like surface area and curvature of gas-liquid interfaces, on flow and transport in porous media; and (3) provide accurate data sets for validation of pore-scale modeling approaches, such as network and Lattice-Boltzmann type numerical modeling. In this report, we present a few examples of images and the sort of quantitative information that can be obtained with the CMT technique.

Methods and Materials

We have used the GSECARS (sector 13) CMT instrument to scan cylindrical samples of sand-packs (with 6- and 1.5-mm inside diameters) during drainage and wetting. The flow experiments are performed while the sample is mounted on the stage, and both capillary pressures and saturation levels are measured continuously during the experiment. By adding a dopant (KI) to the fluid phase and scanning at the peak absorption energy for iodide (33 keV), 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.

Results

An example of a drainage-wetting experiment is illustrated in Fig. 1. The figure shows a horizontal slice through the center of a 6-mm-diameter packed-sand core scanned during various stages of draining or wetting. In the figure, the highest attenuation represents the doped water phase, gray represents sand grains, and black is the air phase. It is obvious from the figure that there are major differences in the distribution of water and air in the sample during drainage and wetting, even though the average sample saturation is the same. Also, individual pores and interfacial curvatures, as well as liquid bridges, can be identified in the images.

Figure 2 shows vertical profiles of linear attenuation coefficients for two different-sized sample-containers (6- and 1.5-mm inside diameters) packed with the same sand (Lincoln fine sand). The figure shows both the differences in the visual level of information for the two sizes and also, very importantly, the quantitative differences in the flow processes in the two sample containers. In the 6-mm-diameter sample, we observe large variations between fast and slow drainage. This is not seen in the smaller sample, however, possibly because of edge effects, but more likely because the container is too small to hold a representative number of grains to adequately represent the flow process.

This effect is illustrated in Fig. 3 with a representative elementary volume (REV) analysis of the two samples with respect to linear attenuation. A cube of $3 \times 3 \times 3$ voxels is grown from the center of each volume, and the linear attenuation coefficient is calculated for increasingly larger voxel volumes. Figure 3 shows that a steady value is never reached within the limits of the smaller sample volume, but the criterion is fulfilled for the larger sample.

Through image processing (cluster analysis), it is possible to separate the three phases (sand, air, water) in the images and thereby quantify each phase separately. An example is illustrated in Fig. 4, which shows 3-D changes in air-phase locations and amounts as a function of water saturation. As occurred in the 2-D multiphase representation (Fig. 1), there are large variations between the drainage and wetting processes at similar saturation levels. Once the sample is resaturated again, the air phase is much more continuous, and the average air-bubble size is significantly larger than it was when the drainage process was started.

Discussion

In our recent work, we have shown that microtomography provides an exciting opportunity for exploring the relationships among capillary pressure, saturation, and air-water-solid interfacial areas and curvatures. In addition to helping us understand previously observed differences between static and dynamic flow processes [1], microtomography provides us with new quantitative constraints on thermodynamic relationships for multiphase flow, such as those developed by Gray and Hassanizadeh (e.g., see Reference 2). Their work challenges the traditional relationship, in which capillary pressure is a function of saturation alone. This hypothesis has not yet been verified through physical experimentation because of the problems associated with measuring the interfacial area in an opaque porous medium. The ability to image pore-scale processes will also enable us to verify recently developed network (e.g., see Reference 3) or Lattice-Boltzmann (e.g., see Reference 4) modeling techniques for describing multiphase flow and transport on this scale.

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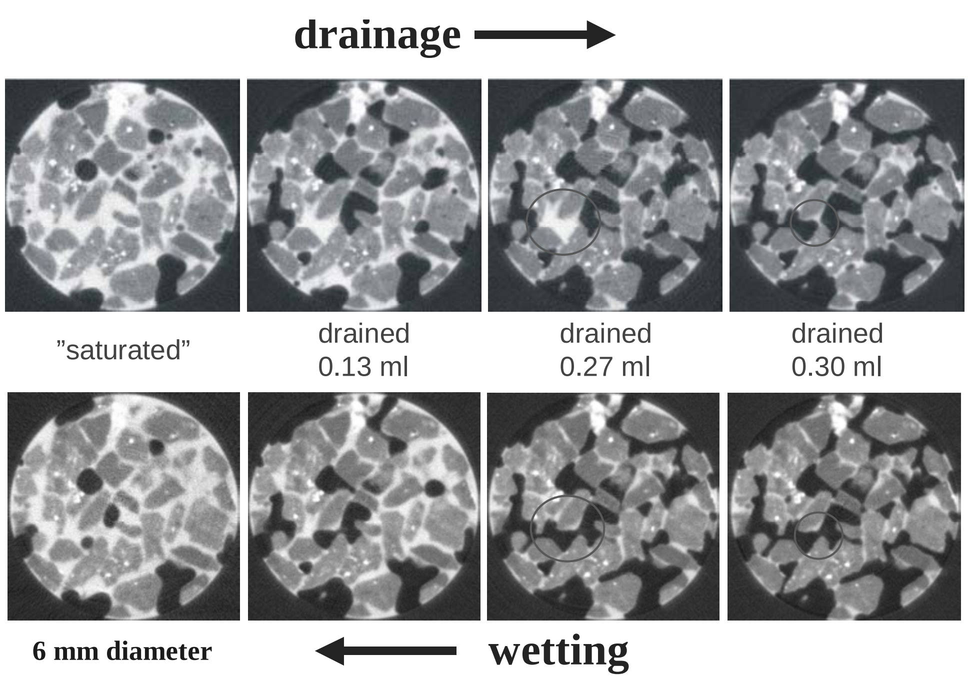

FIG. 1. Horizontal slice through a 6-mm-diameter sand-pack, drained and resaturated in steps to the same sample-average saturation levels.

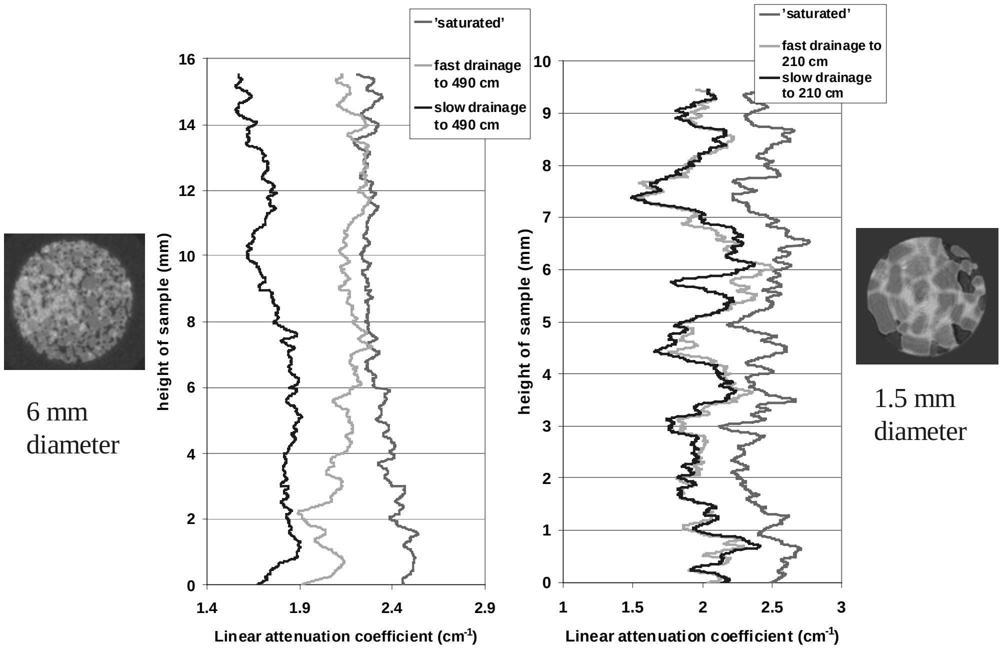

FIG. 2. Vertical profiles of linear attenuation coefficient for two different-sized samples (6- and 1.5-mm inside diameters).

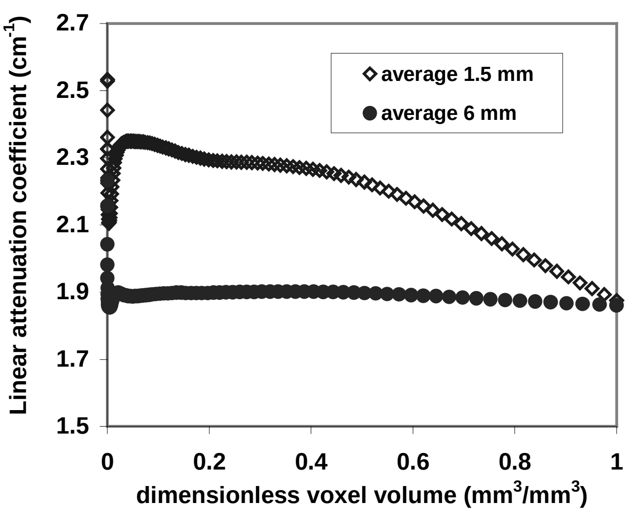

FIG. 3. REV analysis with respect to linear attenuation coefficient for a 6-mm and a 1.5-mm sample consisting of the same sand.

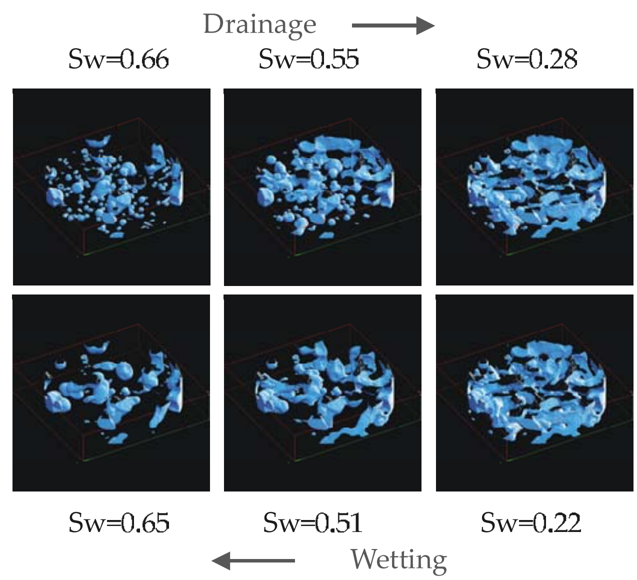

FIG. 4. 3-D illustration of changes in air-phase saturation, location, and continuity as a function of water saturation (Sw).