Using X-ray Microtomography to Quantify Pore-scale Parameters

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Introduction

The pore-scale distribution of fluids in porous media and their variation in time and space prescribe continuum-scale properties, such as capillary pressure-saturation relationships and relative permeabilities. Such continuum-scale properties are used to describe both multiphase flow processes and contaminant transport in porous media. However, capillary pressure-saturation relationships, as well as relative permeability relationships, are hysteretic in nature due to a lack of knowledge concerning basic pore-scale physical processes and how those processes impact flow at the continuum scale. Consequently, measurement of pore-scale properties is necessary to achieve a basic comprehension of the flow processes in porous media. Pore-scale flow and transport mechanisms cannot be measured by using traditional techniques, which usually require a sensor to be inserted at or near the region of interest. X-ray computed microtomography (CMT) overcomes this problem by allowing the noninvasive observation of changing fluid-phase contents and configurations.

Over the past four years, we have conducted microtomography work at the GSECARS sector at the APS to investigate the flow of fluid and gas phases in porous media. A number of experimental conditions have been used to enhance our understanding of pore-scale flow physics. The work has been motivated by a need (1) to understand the differences between static and dynamic flow phenomena; (2) to quantify and better understand the influence of fluid-fluid interfacial properties, such as surface area and curvature, on flow and transport in porous media; and (3) for accurate data sets that can be used to validate the results of pore-scale numerical modeling techniques, like pore network modeling and Lattice-Boltzmann simulations.

This report presents a few examples of images obtained from using x-ray computed microtomography and some results of the experiments conducted.

Methods and Materials

We used the GSECARS (sector 13) CMT instrument to investigate air-water flow through a 7.0-mm internal-diameter cylindrical column packed with glass beads. The flow experiments were performed with the sample mounted on the stage. The saturation level was controlled via the use of a syringe pump connected to the sample, and pressure measurements were recorded continuously during the course of the experiments. A KI dopant was added to the water phase, and the sample was scanned just above the peak photoelectric absorption for iodide (33.2 keV). The addition of the dopant to the water phase allowed us to achieve a level of contrast between the air and water phases that was sufficient to permit the resolution of the phases under varying flow conditions.

Results

An example of a partially saturated sample is given in Fig. 1. This figure shows a lateral cross section of the glass-bead-packed, 7.0-mm-diameter column. The image was taken during primary drainage at a water phase saturation of 72%. In the figure, the regions with the highest attenuation (almost white) represent the KI-doped water phase, the gray areas are sand grains, and the black regions represent air. The figure can then be segmented by using a segmentation routine written in IDL. The image is also cropped in order to reduce the presence of wall effects in subsequent calculations. The

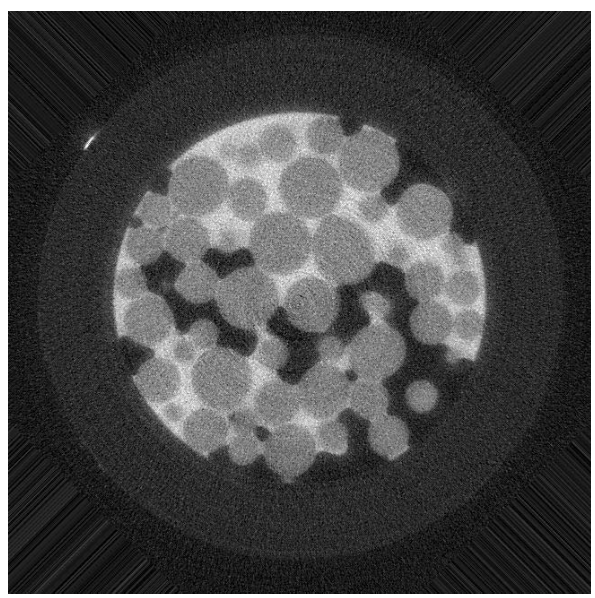

FIG. 1. Lateral cross section of glass-bead-packed column.

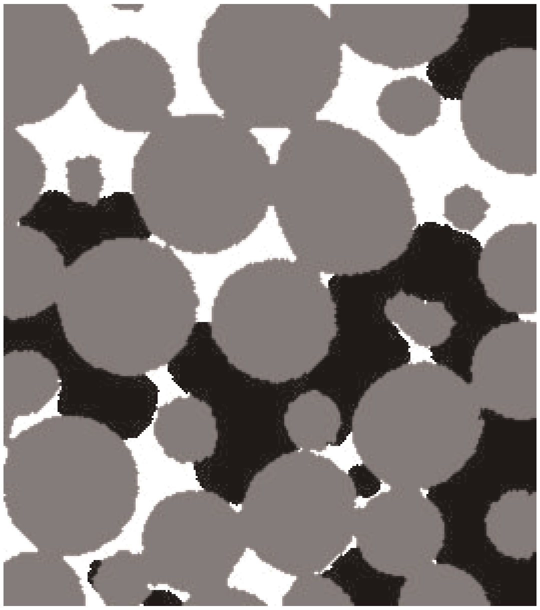

FIG. 2. Segmented subset of original data.

result of this procedure can be seen in Fig. 2.

After the images in IDL were segmented and cropped, a commercial image analysis program, Amira™, was used to compute the air-water interfacial area. Amira uses a modified marching cubes algorithm to generate an isosurface between phases. Figure 3 shows the isosurfaces generated between water and air+solid (a^w), air and water+solid (a^n), and air and solid (a^s). For each saturation at which an image is collected, these three isosurfaces can be combined to compute the air-water (a^{wn}) interfacial area according to:

$$a^{wn} = \frac{1}{2}\left(a^w + a^n - a^s\right) \quad . \qquad (1)$$

The variation of interfacial area with saturation is shown in Fig. 4. As can be seen, the air-water interfacial area increases with decreasing saturation until a maximum is reached somewhere between 20% and 35% saturation, at which point the interfacial area begins to decrease as the saturation goes to zero. Given the resolution of the images obtained (17 μm per pixel), the presence of fluid films on the solid surfaces (on the order of angstroms to microns thick) were below the level of detection and did not contribute to the measured air-water interfacial area. Thus, the results shown in Fig. 4 were expected and confirm numerical pore-scale modeling results presented by Reeves and Celia [1], Berkowitz and Hansen [2], and Dalla et al. [3].

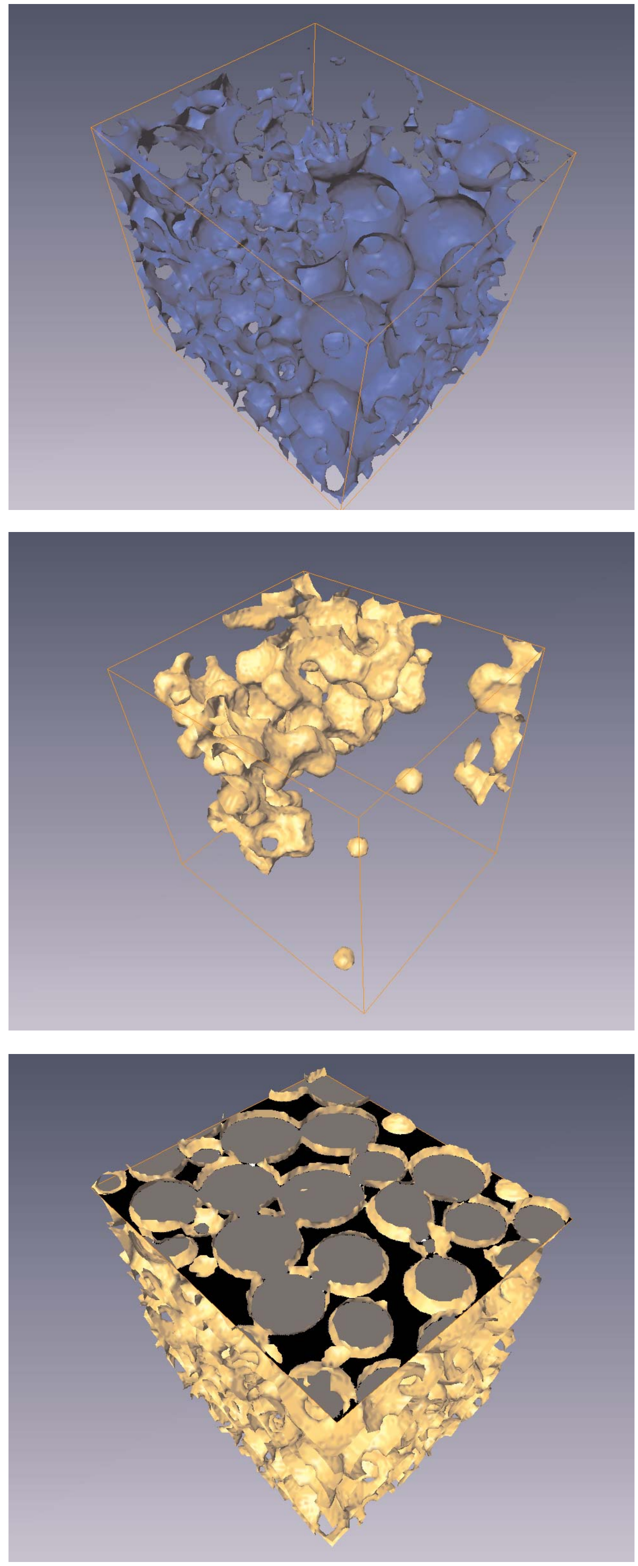

FIG. 3. Isosurfaces for the water, air, and solid, respectively.

Discussion

By using x-ray microtomography, we have been able to obtain fully 3-D images of air-water flow through a porous medium. These images have subsequently been used to compute previously unavailable pore-scale parameters like fluid-fluid interfacial area. The interfacial area measurements provide experimental support for the continued development and verification of a thermodynamically based theory of multiphase flow in porous media (e.g., Gray et al. [4]). This theory challenges the assumption that capillary pressure is a function of saturation alone. Rather, the capillary pressure depends on a number of variables that are currently missing from the functional dependence, the most important of which is the fluid-fluid interfacial area. Heretofore, pore-scale experimental verification of this theory was not been possible because of the difficulties associated with interfacial area measurement in an opaque medium.

The ability to image pore-scale flow processes will enable us, in the future, to provide detailed geometries that can be used as inputs to Lattice-Boltzmann modeling. Experimental results can then be used to verify the output of the Lattice-Boltzmann simulations.

Acknowledgments

Use of the APS was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

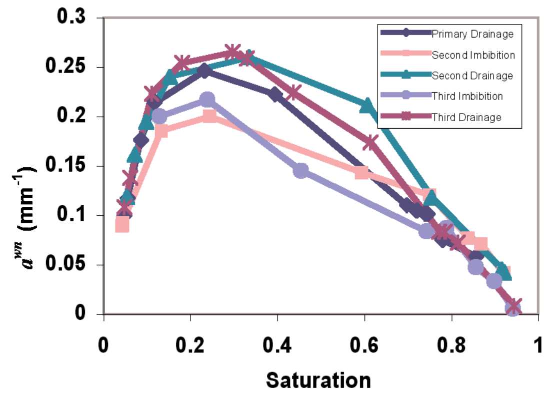

FIG. 4. Interfacial area per volume measurements with respect to saturation for primary drainage, secondary imbibition and drainage, and third imbibition and drainage.

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