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Porous structure and fluid partitioning in polyethylene cores from 3D X-ray microtomographic imaging

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Abstract

Using oil–wet polyethylene core models, we present the development of robust throat finding techniques for the extraction, from X-ray microtomographic images, of a pore network description of porous media having porosity up to 50%. Measurements of volume, surface area, shape factor, and principal diameters are extracted for pores and area, shape factor and principal diameters for throats. We also present results on the partitioning of wetting and non-wetting phases in the pore space at fixed volume increments of the injected fluid during a complete cycle of drainage and imbibition. We compare these results with fixed fractional flow injection, where wetting and non-wetting phase are simultaneously injected at fixed volume ratio. Finally we demonstrate the ability to differentiate three fluid phases (oil, water, air) in the pore space.

Keywords: Porous media; Pore network models; Pore microstructure; Fluid displacement; Drainage; Imbibition

1. Introduction

The development of computational methods to analyze the three-dimensional (3D) microstructure of porous media [1–13] has experienced tremendous invigoration with the advent of synchrotron X-ray computed microtomography (CT) [14], specifically since CT produces huge quantities of 3D data sets, at micron scale resolution in, relatively speaking, short time. It is now fairly common practice to perform fluid transport simulations (e.g. [11,15–22]) in medium realizations based upon 3D CT images. More recently CT technology has been extended to the ability to contrast fluids in the pore space of core samples (air–water in sand packs [23], oil–water in Berea cores [24–26], oil–water in sand packs [27], oil–water in glass bead packs [28], and air–oil in Berea cores [29]), and therefore to the study of fluid partitioning in the 3D pore space. Such studies have the promise to contribute necessary model verification data for fluid transport simulations as well as fluid parameter input (e.g., interphase surface contact areas) for transport models. As CT imaging times are much longer than flow time scales, CT imaging of fluids must be done at a fixed fluid state. Such studies have been done at residual fluid conditions. In this study, we report on fluid partitioning during a complete drainage and imbibition cycle during which CT images were taken after fixed volumes of displacing fluid were incrementally injected. We also report on a second study in which images were obtained after large volumes of both non-wetting and wetting phase were simultaneously injected at fixed volume ratio (fixed fractional flow conditions).

These studies were performed in strongly oil–wet, polyethylene cores. The average pore size in the cores is representative of sandstone standards such as Berea and Fontainebleau; however the polyethylene grain is very homogeneous, which is most desirable for CT studies. In addition, the polyethylene surface is much smoother than is the grain surface in sandstones, simplifying issues relative to surface wetting. On the negative side, the 40–50% porosity of such cores is at least twice that of

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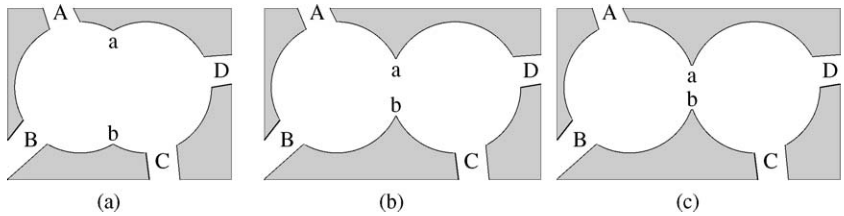

Fig. 1. An illustration of the intuitive difficulty in determining single pore bodies. In each subfigure, void space (white) is accessed through four channels entering at A, B, C and D.

sandstone standards, but is comparable to unconsolidated media.

The larger porosity of these polyethylene cores forces the exploration of a second issue in addition to addressing fluid partitioning. It is standard thinking, and indeed standard practice in network flow modeling, to regard the void structure in geological porous media as a network of pore bodies ("pores" for short) connected to each other via channels. A number of numerical algorithms have been developed [1,3–10,12,13] to analyze CT images and extract pore–channel (or pore–throat) networks.

Central to all algorithms is the labeling of each pore voxel with a value which measures the distance to the closest grain voxel. The pore medial axis (or skeleton) is a minimal deformation retract of the void space which preserves topological properties of the pore space and is centrally located along the pore space. The medial axis (MA) can be organized into paths and branch clusters, utilizing either 26-adjacency or λ-adjacency [8]. The backbone of the MA has all (non-exiting) dead-end paths pruned.

Early attempts used property measurements from the MA backbone to characterize the pore space in reconstructed rock [1] and CT images of real rock [4]. Existing algorithms to extract pore networks can be classified into two types, pore-body detecting [5,9,10,13] and throat constructing [3,6,8,12]. Algorithms of the former type locate pore bodies first and throats secondarily. With one exception, all existing methods construct pores around voxels having local maximum in the distance measure (and throats around voxels having local minimum in the distance measure). The algorithms differ on the details by which neighboring void voxels are uniquely associated to a particular maximum and how neighborhoods may be further merged, resulting in a final set of pores. The exception [9] is based upon Delaunay tessellation. The method has only been demonstrated for regular sphere packings; extension of the method to real porous media is difficult. Throat constructing algorithms consist of two steps, locating the throat position and constructing the throat surface. The constructed throat surface is either planar or non-planar. As the orientation of a planar throat is defined by a single (normal) direction, planar throat surface finding is done either by testing in a fixed, finite number of directions (the multi-orientation scanning method of Zhao et al. [3] and earlier similar works [30–32]) or by determining the normal from the MA [8]. Planar throats are located at positions where (an approximation to) the hydraulic radius is locally minimum. Throat constructions in [7] and [12] are based upon the location and construction of minimal area throats; the throat surface is not restricted to be planar.

Cores of 40–50% porosity present a particular challenge to pore partitioning algorithms. The specific issue is the problem of extracting a pore–throat network that is both geometrically consistent and intuitively correct. As there is a strong complementarity between finding throats or finding pore bodies as the principal algorithmic implementation, this issue is germane to either approach.

We argue that throat assignments should be geometrically consistent; specifically each throat should separate exactly two pore bodies and throats should not cross each other (though touching is possible). In the network algorithms currently in use, there appears to be no guarantee in any algorithm that throat geometries (either when found explicitly or implicitly) will enforce the two-body separation requirement without crossing. (As an example, though the pore-body finding algorithm based upon inscribed spheres [10] guarantees pairwise touching of pores, it is *assumed* that if one pore connects to n other pores, it does so through n separate throats. Inscribed sphere fitting ignores some fraction of the void space. In this ignored region, no checking is performed to determine whether the geometric positioning and orientation of the n throats implies they are indeed separate and do not cross.) Pore-network finding algorithms have typically been verified on sphere packings (ranging from hexagonally close packed to cubic packed) which repeat a unit cell that consists of non-crossing throats. In general these algorithms then work well on low porosity porous media which are roughly "comparable in geometrical complexity" to such packings. However, we find that the complexity in real media produces unexpected geometries.

By intuitively correct networks, we refer to the question of determining whether a region of void space is to be considered a single pore or more than one pore. Fig. 1 uses a 2D example to illustrate that such judgments are use-specific. The figure illustrates three example void spaces. The question of whether the void space in each case is to be considered a single pore or two bodies, i.e. whether the cross section a–b is considered as a throat, is subjective. From a geometric perspective, in which a throat is considered to be a cross section of local minimum hydraulic radius (the ratio of cross-sectional area:perimeter) [41], all three examples would be considered as showing two pores. In all three illustrations, the cross section a–b has been sketched to have larger hydraulic radius than any of the four channel openings. Therefore from the perspective of primary drainage (the void space is occupied by wetting fluid and is to be displaced by non-wetting fluid via one of the connecting channels), the entire void space will be invaded by non-wetting fluid, implying that the void space is acting as a single pore.