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Pore structure of shale

Q1 A. Sakhaee-Pour [a,*], Steven L. Bryant [b]

[a] *Petroleum and Geological Engineering, The University of Oklahoma, OK, USA*
[b] *Petroleum and Geosystems Engineering, The University of Texas at Austin, TX, USA*

HIGHLIGHTS

- We develop a new theoretical void model (i.e., acyclic).
- The acyclic model can capture the non-plateau-like drainage data.
- The acyclic model accounts for the presence of dead-end pores.
- The acyclic model is more realistic for the void space of a gas shale.

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ABSTRACT

Pore connectivity is limited in shale formations, unlike in conventional reservoirs, for which cyclic void models, such as the regular-lattice model, are often used to represent the connectivity. In the cyclic models, the random assignment of throat sizes to lattice elements leads to a plateau-like variation of a capillary pressure with wetting phase saturation during a drainage displacement. Here, we develop acyclic void models in which the spatial distribution of throat sizes is not random. For certain spatial distributions these models yield a non-plateau-like drainage displacement. Such models thus provide more realistic representations of the void space in samples for which drainage experiments reveal the non-plateau-like trend of the capillary pressure versus saturation. Gas shales commonly show such a trend, and using the developed models, we predict the no-slip permeability of shale samples whose mercury intrusion capillary pressures curves were measured under confined boundary conditions. The predicted permeabilities are in good agreement with the lab measurements reported for these samples. Other models either fail to account for the non-plateau-like trend of the drainage as they adopt a random pore size distribution or they overestimate the no-slip permeability for saturated flow. The models developed here could have application in other porous media whose drainage data do not exhibit a plateau-like variation.

1. Introduction

Network modeling is a field of study concerned with the analysis of the flow through porous media. This field classifies the void space into pores and pore throats, and then investigates the interactions between the pores. The interactions between the pores take place through the pore throats, which are often defined the narrowest region of the void space between two neighboring pores. The spatial distribution and hydraulic conductances of the throats govern the overall flow properties of the model. This analysis is at pore-scale, which is smaller than the core-scale at which most lab measurements are reported. Fig. 1 shows a schematic of the network modeling.

We classify the network modeling approaches into theoretical and non-theoretical. The theoretical approach hypothesizes a spatial distribution of the pore throats relative to each other a priori, and then tests whether the adopted distribution is consistent with the measured data [1–7]. The spatial distribution of the throats is relevant to the connectivity of the pores. The non-theoretical approach makes no assumption about the spatial distribution and extracts the pattern of the connected pores from the scanning electron microscopy (SEM) images [8] or from high resolution X-ray computed tomography [9,10]. Empirical models are non-theoretical as well because they do not assume a spatial distribution for the pore throats relative to each other a priori. The empirical models on the single-phase permeability are proposed to correlate the saturated permeability to drainage data [11]. Since the main focus of the present study is theoretical, we review only the theoretical models here but a thorough review of

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Q2 * Corresponding author.
E-mail address: sakhaee@ou.edu (A. Sakhaee-Pour).

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the empirical models could be found in a study conducted by Comisky et al. [12].

Washburn [13] set forth the first theoretical void model, proposing that a bundle-of-tubes model could mimic the void space. Later, Purcell [1] used this approach to predict flow properties. The main advantage of the bundle-of-tubes model is its simplicity; its disadvantage is that it disregards the interconnectivity of the pores (Fig. 2(a)).

Fatt [2] developed another theoretical network model in which he introduced the notion of interconnectivity. He proposed that the pores are interconnected in a regular-lattice pattern. This means that spatial distribution of the pore throats is similar to the regular lattice. Fig. 2(b) shows a schematic of a regular-lattice model as an example. This model is popular because it allows us to capture two-phase flow properties and yet is relatively easy to implement [6,14,15].

Another theoretical approach assumes that spheres can represent the grains of a sedimentary rock, and thus the empty spaces between them mimic the void space of the porous medium. Finney [16] measured the spatial coordinates of a random packing of ball bearings that were used later for this type of analysis. In this approach, the network model is obtained by knowing the locations of voids in the packing. From this notion, Bryant et al. [3] developed a physically representative model where they evaluated permeability and spatial correlation of an unconsolidated porous medium from the network modeling approach. Using the representative model, researchers also examined the effects of grain sedimentation, compaction, and diagenesis on transport properties [4,8]. Recently, Mousavi and Bryant [17] used this model to capture two-phase displacement in a tight gas sandstone when the fraction of microporosity is not significant. In general, this model has more application for unconsolidated sandstones.

Pore throat geometry is a crucial parameter in the network modeling approach. It controls the hydraulic conductance of the throats, which in turn controls the interactions among pores. The bundle-of-tubes and regular-lattice models often assume a circular tube for the throat geometry. Pore throat geometry, however, can be more generally rectangular and triangular [18]. Throat geometries with sharp corners enable us to better capture residual phase saturations [18]. The most general throat geometries (irregular cross section that converges and diverges from one pore to the next) arise in the sphere packing models.

In the present study, we develop theoretical pore models in which the spatial distributions of the throats are acyclic and the throats have circular or slit-like throat geometry. The developed models are acyclic in a graph theoretic sense, in which a cycle is a path that starts and ends at the same node without retracing any bond. The acyclic models are fundamentally different from cyclic models such as regular lattice and sphere packing in which there are at least two paths between any two pores in their structures. The Bethe lattice [19] is the classic example of an acyclic graph; trees are the most familiar natural example. The acyclic void model could help us build a more realistic representation for the void space. This is crucial in terms of understanding hydrocarbon distribution in the void space, pace of recovery, and ultimate recovery in tight formations. The authors showed such an example by studying the effect of pore structure on the producibility of tight gas sandstones [20].

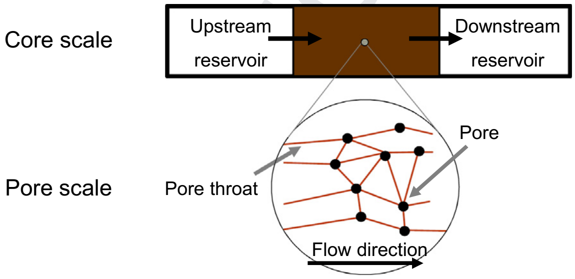

Fig. 1. Schematic of the network modeling approach at pore-scale, which is smaller than the core-scale for which most lab measurements are reported. Black circles denote pores and red lines represent the pore throats. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

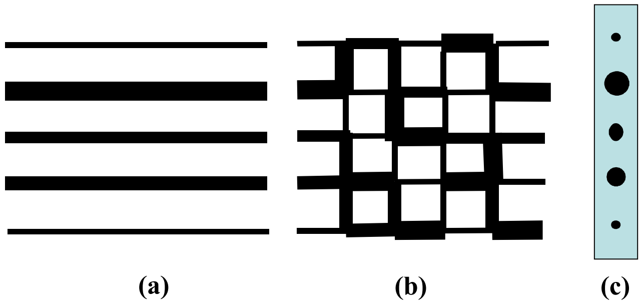

Fig. 2. (a) The bundle-of-tubes model [1,13] in which the void space is represented by parallel tubes; (b) is the schematic of a two-dimensional regular-lattice model in which [2] introduced the notion of interconnectivity; (c) is the side view of the left sides of the models in which throats are circular.

Of particular interest for our application, the acyclic model allows us to capture a non-plateau-like trend of capillary pressure versus wetting-phase saturation. We then use our model to predict the no-slip permeability of confined shale samples whose drainage data are available in the literature. This is because of the growing interest in better understanding of the transport properties of these formations [21].

2. Pore space characterization

The theoretical network modeling approach seeks to characterize the pore space; this embraces specifying throat sizes and their spatial distribution. Fig. 2 illustrates these two elements. To build a realistic representation, the theoretical modeling approach investigates lab measurements such as mercury intrusion and permeability.

2.1. Non-plateau-like capillary pressure

During mercury intrusion, the capillary pressure (P_c) is increased incrementally and the increase in the mercury saturation (S_{Hg}) is measured [22,23]. The decrease of the wetting phase saturation (S_w) is determined from the increase in the mercury saturation ($S_w = 1 - S_{Hg}$). At each capillary pressure, throats whose characteristic sizes are larger than or equal to the corresponding capillary pressure could be invaded. Of these, however, only those that are accessible to the nonwetting phase actually are invaded (Fig. 3).

In cyclic models, at some capillary pressure, a significant number of throats are invaded. Compare Fig. 3(a2) and (a3). The nonwetting phase can invade those throats at a lower pressure if the throats are alone, but they are not directly accessible to the nonwetting phase at a lower pressure. This invasion of a significant number of throats leads to a notable decrease in the wetting phase saturation over a small change in the capillary pressure. This appears as a plateau-like trend in the capillary pressure measurements, as Fig. 3b shows. This phenomenon results from the random distribution of the throats in the cyclic model.

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