Calibration of a Pore-Network Model by a Pore-Morphological Analysis

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Abstract. Calibrating the geometry of a pore-network model is a challenging task if such a model is sought to make quantitative predictions for an experimental porous medium system. Our calibration approach maps a digital representation of a porous medium’s microscopic pore geometry onto the size distributions for the pore bodies and pore throats and onto the coordination number of the network. This is accomplished by matching the morphological pore-size distribution and the genus of the network with those of the porous medium. The microscopic pore geometries were obtained by simulating random sphere packings, which match the grain-size distribution and the porosity of the experimental porous media. We obtained good agreement between simulated and measured hysteretic capillary pressure–saturation curves for three porous media. Correlations between pore-body and pore-throat sizes were important to achieve a realistic description of the simulated imbibition scanning curves.

Key words: calibration, capillary pressure, hysteresis, multiphase flow, network model.

1. Introduction

Pore-scale modeling of fluid flow in natural porous media is a challenging task because of the complicated pore geometry typical of such systems. In order to simulate large domains, one often represents a porous medium by a pore-network model (Blunt, 2001), such as spheres that are connected by cylinders. Fluid flow can then be described by the Poiseuille equation for the viscous pressure drop and the Laplace equation for the capillary pressure but need not be simulated by continuum or molecular equations.

The difficulty in using pore-network models for quantitative predictions is the choice of their geometry, that is, the sizes, locations, and orientations of the pore bodies and pore throats. This task can be accomplished by (1) relating the pore-space morphology to measured capillary pressure–wetting phase saturation ($p_c$–$s_w$) curves (Chatzis and Dullien, 1977; D’Hollander, 1979; Jonas and Schopper, 1994), (2) fitting measured $p_c$–$s_w$ curves to simulated ones (Fischer and Celia, 1999;
Hilpert et al., 2001), (3) obtaining a three-dimensional digital representation of the pore space and identifying the actual positions and sizes of the pore bodies and pore throats (MacDonald et al., 1986; Bryant and Blunt, 1992; Bakke and Oren, 1997; Bekri et al., 2000), or (4) obtaining a three-dimensional digital representation of the pore space and mapping this information onto the statistical properties of the pore bodies and pore throats (Lymberopoulos and Payatakes, 1992; Vogel and Roth, 1998, 2001; Tsakiroglou and Payatakes, 2000). In the last two methods, the digital representation of the pore space may either be measured directly – using, for example, tomographic means or the serial-section technique – or be stochastically reconstructed.

In this work, we pursue this fourth method by modifying the work of Vogel and Roth (1998), who calibrated a pore-throat network by analyzing for the morphological pore-size distribution and the connectivity of the pore space. We develop a calibration approach for pore networks consisting of both pore bodies and throats by analyzing the morphology of three-dimensional digital representations of porous media. We compare measured hysteretic $p_c$–$s_w$ curves with those simulated in the calibrated networks.

2. Methods

2.1. OVERVIEW

Once the network structure, that is, the shape of the network elements and the locations of the pore bodies and their connectivity via pore throats, are chosen, the network geometry needs to be quantified. One has to specify (1) the pore-body size distribution; (2) the pore-throat size distribution; (3) the coordination number; (4) the spatial correlation structure between pore bodies and pore throats; and (5) the lattice constant. Using the following steps, our calibration approach for pore networks yields these quantities by using only the grain-size distribution and the porous medium’s porosity:

1. We simulate a random sphere packing, which matches the grain-size statistics and the porosity of the experimental porous medium, using the sphere-packing algorithm and computer code developed by Yang et al. (1996). From its output, the centers and diameters of the spheres, we then obtain a digital representation of the packing.

2. We determine integral geometric properties that represent the pore space’s morphology: the morphological pore-size distribution and the genus. Section 2.2 describes details of this task.

3. We calibrate the pore-network model by matching these integral properties with those of the network. Section 2.3 describes in detail the network morphology and Section 2.5 the calibration approach.

4. We then simulate hysteretic $p_c$–$s_w$ curves as described in Section 2.4.