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Prediction of imbibition in unconsolidated granular materials

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Abstract

A new way of modeling imbibition is proposed in this paper. It combines two elements. One is a physically consistent, dynamic criterion for the imbibition of an individual pore originally suggested by Melrose (SPEJ (November 1965) 259–271). The other is the use of a simple but physically representative model of porous media: a dense random packing of spheres that is geometrically predetermined. This approach allows truly a priori predictions of imbibition curves (saturation vs capillary pressure) for different values of contact angle, different initial conditions (e.g., different drainage endpoints), and different macroscopic sample geometries (the ratio of external to internal pores). It also provides a mechanistic basis for understanding the influence of pore-scale phenomena such as "snap-off" of nonwetting phase in the pore throats due to the coalescence of pendular rings. The simulations show that the capillary pressure curve for this unconsolidated packing is very sensitive to the wettability parameters (such as contact angle), whereas the influence of different initial conditions and snap-off is almost negligible. Predicted capillary pressure curves are compared to experimental data presented in the literature, and are consistent with them.

Keywords: Porous media; Imbibition; Finney packing; Snap-off; Meniscus; Residual saturation

1. Introduction

The properties of porous media have a great importance for the modeling and understanding of different flow processes in the subsurface, such as oil recovery, drainage and imbibition, infiltration from surface water, and flow, transport, adsorption and dissolution of contaminants. Because of the great influence of these processes on the environment and industry, there have been numerous attempts to model them at the microscopic scale and to predict the behavior of the subsurface. Many of these attempts model the porous medium as a *network* with *sites* (pore bodies) and *bonds* (pore throats) and some parameters prescribed to the network in advance, for instance, *coordination number* of the sites or *size distribution* of pore bodies and pore throats. By simulating transport processes in such networks one can describe the behavior of the desired unknowns (i.e., relative permeabilities, residual NAPL saturation, dissolution rates, etc.). These network models have been used to study a wide range of the properties in different flow processes, such as relative permeabilities [15,50]; residual nonwetting phase [35]; capillary pressure hysteresis [26,27,31,42]; relationships between capillary pressure, saturation and interfacial areas [6,51]; non-Darcy behavior [62]. Unfortunately, the *predictive* capability of this approach is limited by the presence of prescribed parameters, which usually cannot be determined independently of the phenomena of interest.

The approach considered in this work is similarly devoted to the pore-scale modeling of the flow and transport processes in the subsurface, but it differs significantly from network modeling. The idea is to extract a faithful representation of the actual pore space geometry of a simple but *physically representative* model porous medium [8,10–12,37,38]. The model is a random packing of equal spheres for which the coordinates of the centers have been measured (*Finney pack* [14]). Knowledge of the coordinates completely deter-

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mines the grain space and the void space in the packing. It is also possible to simulate the results of geologic processes in the sphere pack, such as cementation and compaction, thus creating simple models of sedimentary rocks with predetermined pore space geometry [8,10,12].

This class of models has been shown to capture some of the key features of real sediments and sedimentary rocks [7–9,17,37,60]. Other methods of obtaining detailed, realistic, quantitative models of pore space have been developed, along with sophisticated techniques for computing properties of those models [1,3,4,19,28,30,34,47–49,53,54,59,61]. The imbibition mechanism studied here can be applied in any member of this class of geometrically determinate models. Our purpose is to test the macroscopic implications of a pore-level imbibition mechanism. Sphere-pack models are well suited for this purpose. They are a computationally convenient framework for making *a priori* predictions of macroscopic behavior. Because there are no prescribed parameters, testing the predictions against experiments provides physical insight.

If the predictions do not explain experimental observations, we can conclude that the model does not account for some essential aspect of the physical situation, and then seek a more realistic model. On the other hand, a successful prediction allows some confidence that the model can be taken as a reasonable approximation of reality, and thus has a predictive capability and can be used to examine other phenomena. This capability, rather than understanding the behavior of a particular sample(s), is the focus of this paper.

The model of imbibition presented in this paper is based on the methodology developed in [7–9,17,37]. Knowledge of the pore space geometry and wettability conditions (the value of the contact angle, assumed uniform throughout the medium) allows computing the configuration of two fluid phases in porous media under the control of capillary forces. Then the quasi-static imbibition of a wetting phase in this model porous medium is simulated by means of the dynamic Melrose criterion [41]. To our knowledge, this criterion has not been tested in a geometry representative of granular media. An attractive feature of the Melrose criterion is its purely mechanistic nature. Knowledge of grain scale geometry is the only prerequisite for its application. In this way we hope to provide some insight into the long-standing fundamental problem of how imbibition occurs in a single pore. The approach also allows a quantitative understanding of how different macroscopic processes and parameters (for example, capillary pressure–saturation curve) depend on the physical (e.g., wettability) features of porous media during imbibition.

2. Pore-scale description of an unconsolidated medium

In 1899 Slichter [55] suggested the random packing of equal spheres as an “ideal soil.” Though this approach is surely oversimplified, it nevertheless captures many essential features of the pore space of real sediments, Figs. 1 and 2. The most important of these is the randomness in locations of grains, pores and pore throats. Thus, the “ideal soil” model allows constructing simple, but *physically representative* sediments. Moreover, the geometry of pore space is determined by the geometry of the grains making up the porous medium. It is this dependence that enables the successful predictions described above.

Fig. 1. Fontainebleau sandstone.

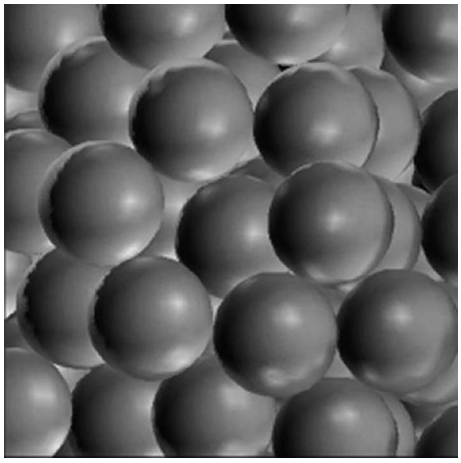

Fig. 2. Random dense packing of equal spheres.

This approach offered useful qualitative insights in the decades after its introduction [18,21–24,56–58]. No quantitative applications involving genuinely random packings were possible, however, until Finney [14] measured spatial coordinates of the centers of about 8000 randomly packed equal spheres, in order to build a model of the liquid state. The power of Finney’s data for the modeling of porous media was quickly recognized and applied by Mason [38]. Later Mellor presented a method (described below) for extracting a network model of the pore space in the Finney packing [39].

The common way of constructing a network model of porous media as a lattice of sites (pores) connected by bonds (pore throats) assumes random assignments of network attributes, such as pore throat and pore body sizes. In real porous media such features are not randomly distributed [8,11] and are difficult to measure. A completely differ-