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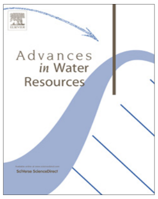

Multi-scale, micro-computed tomography-based pore network models to simulate drainage in heterogeneous rocks

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ABSTRACT

The multi-phase flow behavior of complex rocks with broad pore size distributions often digresses from classical relations. Pore-scale simulation methods can be a great tool to improve the understanding of this behavior. However, the broad range of pore sizes present makes it difficult to gather the experimental input data needed for these simulations and poses great computational challenges. We developed a novel micro-computed-tomography (micro-CT) based dual pore network model (DPNM), which takes microporosity into account in an upscaled fashion using symbolic network elements called micro-links, while treating the macroporosity as a traditional pore network model. The connectivity and conductivity of the microporosity is derived from local information measured on micro-CT scans. Microporous connectivity is allowed both in parallel and in series to the macropore network. We allow macropores to be drained as a consequence of their connection with microporosity, permitting simulations where the macropore network alone does not percolate. The validity of the method is shown by treating an artificial network and a network extracted from a micro-CT scan of Estaillades limestone.

1. Introduction

Over the last few years, pore scale modeling of transport properties in geological materials has gathered enormous momentum. Transport processes in porous media take place at the pore scale, and pore scale simulations have helped to improve the understanding of the behavior of porous media at larger scales. These simulation methods have important applications in, for example, petroleum engineering, environmental remediation in aquifers and CO_2 sequestration, as they help to assess the constitutive relations used as input for field-scale simulations. Blunt et al. [1] and Meakin and Tartakovsky [2] provide excellent reviews on the advancement of pore scale modeling. The growth in this field has been made possible by the rapid improvement in 3D imaging techniques such as laboratory-scale micro-computed tomography (micro-CT) scanners and focused ion beam-scanning electron microscopy (FIB-SEM, [3]) installations. An extensive overview of the current state of 3D micro-CT imaging for geological applications can be found in [4,5]. The accessibility of lab-based micro-CT equipment allows the direct imaging of a rock's pore space in all three dimensions at relatively low cost in relatively short times, down to a voxel resolution on the order of 0.5 μm.

Once a 3D image of a pore space has been obtained, two main approaches to model transport can be discerned: direct modeling and pore network modeling. In direct modeling, the Navier–Stokes equations are solved directly on a gridded or meshed 3D image of the pore space geometry. However, when multiple phases are flowing simultaneously in a rock's pore space, most direct methods are very computationally demanding [2,6]. Therefore, to date the other approach – pore network modeling – has been the most successful at predicting two- and three-phase flow properties based on 3D images of real porous rocks [1].

In pore network models (PNM), a network of pores and throats with idealized geometric shapes is extracted from the "real" pore space represented in the original 3D image of the porous medium [1]. In addition to providing insight into the collective behavior of a complex network of pores which each adhere to certain well-defined (usually relatively simple) rules, pore network models have been shown to possess predictive capabilities to two-phase flow in rocks [7,8]. Two-phase flow in these models is typically simulated using invasion-percolation with the assumption of quasi-static fluid displacement, valid for slow, capillary-dominated flow. A number of studies have shown that despite the loss of detail when assuming the idealized geometric shapes of the network elements and the quasi-static fluid displacement, good results can be obtained providing one uses a network extraction method which captures the real geometry and topology of the pore space well

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[9–15]. Three main types of network extraction methods exist: the grain-based method [16], the medial-axis based method [14] and the maximal-ball based method [9]. PNM simulations are much less computationally demanding than direct methods, allowing researchers to incorporate more heterogeneity by modeling larger rock volumes. As natural geological media can be heterogeneous on all length scales, this is an important advantage of PNM.

Despite the advances of pore scale modeling, the simulation of transport properties in heterogeneous rocks with very broad pore size distributions remains an open-standing issue. Broad pore size distributions are for example found in many types of carbonates and clay-rich sandstones, which are media of considerable economic and scientific importance (e.g. hydrocarbon extraction and CO_2 sequestration in carbonate reservoirs or in tight gas sandstones). The importance of simulations in these types of rock is increased by the failure of most classical empirical relations such as Archie's law for electrical behavior and the Brooks–Corey parameterization of relative permeability [17]. The failure of these relations is due to the interaction of micro-and macroporosity, spurring the development of modeling methods where multiple pore scales are coupled.

1.1. Imaging microporosity

When a rock with a broad pore size distribution is investigated with a 3D imaging technique such as micro-CT scanning, it is often not possible to visualize pores of all scales present in one experiment due to the resolution/sample size trade-off. For the remainder of this work, we define "micropores" as pores which are below the resolution of the micro-CT scan in question. This means that in most cases, micropores are defined as pores with sizes under around 1 to a few micrometers. "Macropores" are then pores which are resolved at that same resolution.

In a micro-CT experiment, the partial volume effect will ensure that, in a mono-mineralic rock, regions with pores smaller than the scan's resolution will show up less bright than solid regions. This is due to the lower effective material density in the former regions. An example of such a micro-CT scan can be found in Fig. 1. In a multi-mineralic rock, differentiating a micro-CT image of the dry rock and a micro-CT image of the rock vacuum-imbibed with a strongly attenuating contrast liquid can allow to visualize microporous regions [18–20]. Therefore, micro-CT scans can be used to investigate the connectivity of macropores to microporous zones, even if the resolution is insufficient to investigate the geometry or connectivity of individual micropores.

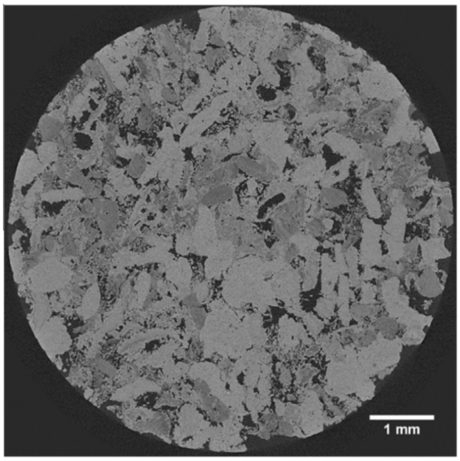

Fig. 1. Reconstructed slice from a micro-CT scan of Estaillades limestone, with a voxel size of 3.1 μm. The sample's diameter is 7 mm. Dark grey regions contain sub-resolution microporosity, while light grey grains are solid calcite.

1.2. Multi-scale modeling

Modeling of multi-phase flow in porous media with very wide pore size distributions has proven to be challenging, as the necessary resolution of such a model is dictated by the smallest pores of importance, while the minimal size of the model is dictated by the representative elementary volume (see for example [21]) of the medium. The resolution/size trade-off, both in imaging and modeling, makes that PNM are the most likely candidates to simulate transport in such media, due to their computational efficiency and their infinite resolution. PNM specially adapted to this problem are often referred to as dual pore network models (DPNM). A short overview of existing work on these models is presented here (see Fig. 2).

Jiang et al. [22] developed a workflow to integrate networks extracted from images at different resolutions. A PNM of arbitrary volume representing the microporosity is statistically generated based on a small network extracted from high-resolution imaging or modeled data [26]. A network representing the macropores is then fused with the microporosity network by characterizing the cross-scale connection structure between the two networks. In principle, networks of multiple scales can be fused this way, however, a drawback of this method is that the number of network elements can quickly become computationally prohibitive. Mehmani and Prodanović [17] and Prodanović et al. [23] follow a similar network fusion approach but pay more attention to the location of microporosity. They use a more ad-hoc approach to generate microporous networks by downscaling existing networks extracted from macropores. However, using their DPNM, they were able to investigate fundamental two-phase flow properties of multiscale porous media, and they distinguish a clear difference between the behavior of a system where microporosity acts in series to the macropores (intergranular or pore-filling microporosity) and a system where it acts in parallel (intragranular or dissolution microporosity).

Recognizing the computational problems when single micropores are taken into account, Békri et al. [27] built a DPNM by representing the large pores as a cubic-lattice based PNM, which they supplement with conductivities due to microporosity in the matrix. The microporosity is considered to be a continuum porous medium, acting in parallel to the cubic PNM. They allow large pores to be drained through micropores when a breakthrough capillary pressure is exceeded. Building on the same idea of representing microporosity as a continuous medium, Bauer et al. [25,28] extracted image-based networks of the macroporosity from micro-CT images of carbonate samples and added cubic blocks of microporosity in parallel to a user-defined percentage of macrothroats in this PNM. Although their method is largely image-based, micro- and macroporosity were considered to conduct only in parallel. Contact surface areas of macropores with microporosity, necessary to calculate microporous conductivities, were based on the total contact surface area measured over the entire micro-CT scan.

In this work, we use the approach of treating the microporosity as a continuous porous medium to develop an image-based DPNM extraction method, in which microporosity is allowed to act both in parallel as in series to the macropore network. This is important, as serial microporosity produces very different effects than parallel microporosity, and its impact is harder to estimate a-priori [17]. We derive the connectivity added by microporosity from micro-CT information. A model for the conductivity of microporous connections was developed based on local data measured on the micro-CT image. Our DPNM method allows macropores to be drained if