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Multiscale Generalized Network Modeling of Carbonates with Sub-Resolution Porosity

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With advances in digital rock physics, pore-scale numerical methods have been developed to estimate various petrophysical parameters based on 3D micro-CT images. However, currently pore-scale models mostly rely on segmented dry scan of the rock sample for network extraction, and the resulting network consists only of resolved pores and throats. For complex rocks such as carbonates that encompass multiple length scales, capturing pores at every scale is often not possible due to the size-resolution trade-off. In this study, we develop a multiscale generalized network model (GNM) by including sub-resolution porosity as another throat type, called micro-links, and modify the flow model by including flow through micro-links. In single-scale GNM, resolved throats are the main pore elements in the network and are divided into corners by certain discretization levels. GNM has several benefits, such as realistic representation of the pore space with the effect of throats expanding from throat center to neighboring pore centers and detailed corner description (Raeini et al. 2017). Moreover, GNM improves the physical accuracy of model predictions by formulating the 3D interfacial curvature between two phases not only in the axial plane but also in the sagittal plane (Raeini et al. 2018; Giudici et al. 2023). We employ differential imaging of brine and dry scans to characterize connectivity and quantify unresolved porosity. We obtain a porosity map containing all voxels with their sub-resolution porosities. Using the dilation algorithm developed by Foroughi et al. (2023), each microporous voxel is labeled according to its two closest pores, and then microporous voxels with the same closest pores are classified as a micro-link. Since we consider micro-links as continuous Darcy-like porous media, we use classical empirical relationships to describe flow in micro-links. We first tested our multiscale model with highly permeable Ketton limestone. We tuned our model to mimic the reported Ketton mercury injection capillary pressure (MICP) data, which exhibited a bimodal throat size distribution, one peak at larger pores is attributed to interparticle resolved pores large enough to be captured at micro-CT voxel size, and the peak at small pore size is for intraparticle micropores. And in between, there is an intermediate interval covering unresolved macropores, which are larger than micropores but are under resolution. To achieve a good match with the MICP curve, we determine the critical micro-link porosity as the boundary between different porosity regions and evaluate their saturation exponent and grain diameter values separately. After calibrating the model with measured permeability, formation factor, and MICP data, we generate a bimodal capillary pressure curve for oil drainage into initially water-wet system. Even in the early stages of drainage, we observe an increase in the relative permeability of water, contributed by unresolved porosity. In summary, our approach shows significant promise in addressing sub-resolution porosity in a less computationally costly manner using micro-links. We aim to extend our approach to other complex multiscale systems, including fuel cells, membranes, and batteries.

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