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A Simulation Approach Including Underresolved Scales for Two-Component Fluid Flows in Multiscale Porous Structures

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Abstract. In this study, we develop computational models and a methodology for accurate multicomponent flow simulation in underresolved multiscale porous structures [1]. It is generally impractical to fully resolve the flow in porous structures with large length-scale differences due to the tremendously high computational expense. The flow contributions from underresolved scales should be taken into account with proper physics modeling and simulation processes. Using precomputed physical properties such as the absolute permeability, K_0, the capillary pressure-saturation curve, and the relative permeability, K_r, in typical resolved porous structures, the local fluid force is determined and applied to simulations in the underresolved regions, which are represented by porous media. In this way, accurate flow simulations in multiscale porous structures become feasible.

To evaluate the accuracy and robustness of this method, a set of benchmark test cases are simulated for both single-component and two-component flows in artificially constructed multiscale porous structures. Using comparisons with analytic solutions and results with much finer resolution resolving the porous structures, the simulated results are examined. Indeed, in all cases, the results successfully show high accuracy with proper input of K_0, capillary pressure, and K_r. Specifically, imbibition patterns, entry pressure, residual component patterns, and absolute/relative permeability are accurately captured with this approach.

AMS subject classifications: 52B10, 65D18, 68U05, 68U07

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1 Introduction

The numerical simulation of multicomponent fluid flows in porous regions with complex solid structures is of great importance in many industrial applications such as enhanced

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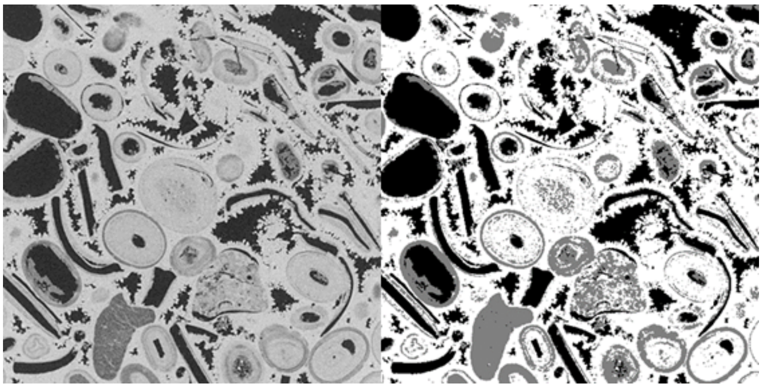

Figure 1: Cross-section pictures of a carbonate rock. An original scanned picture (left) and a segmented picture with small-scale porous structures marked in gray (right) are shown.

oil recovery including carbon dioxide injection, capture and storage [2,3], water/air flow in gas diffusion layers of fuel cells, [4–6], in situ copper mining by leaching [7], and sophisticated personal protective equipment [8]. To achieve high-fidelity simulation, it is crucial to fully resolve complex solid boundaries. In most simulation cases, however, fully resolving all details of a multiscale porous structure is infeasible due to limited machine power and the immaturity of computational models and algorithms, although such complex structures are frequently observed in nature.

Here is an example from an oil&gas industry application. Fig. 1 shows a typical cross-section of a carbonate rock sample that has porous structures with multiple different scales [9]. The left picture shows one slice of an original microtomography scanned image, and the right picture shows its segmented image with small-scale porous structures marked in gray. The length-scale difference between black and gray structures is approximately tenfold. The small-scale porous regions in gray could significantly impact the flow behavior on a large scale because they can contribute to the connectivity among larger-scale pores and can lead to high capillary forces and variable flow resistivity. Therefore, it is necessary to properly consider their contributions. However, resolving all such small-scale details requires extremely fine resolutions, which results in a tremendously expensive simulation. The cost could increase by a factor of tens of thousands compared to the unresolved case, ignoring the contributions of small porous structures from the gray regions because of the increased number of three-dimensional cells and the reduction of time increments. Therefore, such fully resolved simulations are impractical in industrial applications.

In many previous studies [10–16], the viscous force from underresolved porous media (PM) was modeled by a resistance term, as in the Brinkman equation, using a precomputed permeability in the resolved PM with finer resolutions. These studies, however, mainly focused on single-component fluid flow and did not extend to multicomponent fluid flow. A few recent studies [17, 18] have discussed multicomponent fluid flow in multiscale porous structures. In reference [17], the relative permeability from underre-