Toward a New Generation of Two-Fluid-Phase Flow Models: Theory, Computations, Experiments, and Remaining Challenges

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Introduction

A sustained effort by a growing number of researchers over the last quarter century has been aimed at developing a new class of macroscale two-fluid-phase flow models that resolve and evolve not only fluid pressures, saturations, and velocities, but other important measures of the system state, such as interfacial areas. It has been posited that a more complete system state would enable reducing, or removing, hysteresis from the closure relations. Efforts have also been aimed at understanding the role of dynamics in the relaxation of such systems to an equilibrium state. The overall goal of this work is to report on recent theoretical, experimental, and computational advancements to evolve this next generation of model, and to outline the remaining challenges that must be overcome to complete this effort.

Methods

The thermodynamically constrained averaging theory (TCAT) was used to generate a hierarchy of potential two-fluid-phase flow models of varying fidelity, which naturally includes quantities such as interfacial areas, tensions, and curvatures, as well as related terms for common curves [1]. Averaging theorems were used to produce evolution equations to assist in model closure. The TCAT formulation results in the need to determine specific forms of state equations, and closure relation parameters.

Lattice-Boltzmann methods (LBMs) were used to provide the necessary closure information and to evaluate and validate the resultant theory. Toward this end, a variety of experimental, model, and natural porous medium systems were used to evaluate and validate the TCAT models. The LBM simulator was based on a color model, a D3Q19 lattice, and level-set methods to identify and track interface dynamics. Microfluidic experiments were performed to examine two-fluid displacement patterns.

Results

TCAT theory has been used to demonstrate conditions that must hold at equilibrium for two-fluid-phase systems. We show conditions that are necessary for commonly used closure approximations for capillary pressure to hold, and we show such conditions are unlikely to occur. We reinterpret traditional approaches to show approximately what is implicitly assumed and why acceptable results are achieved in some instances. We illustrate hysteresis in light of the common ink-bottle example, and we demonstrate an approach to remove hysteresis in a capillary pressure state equation, which we also show to hold for both equilibrium and dynamic conditions. We also show the importance of momentum transfer across the fluid-fluid interface and use microscale simulations to determine the corresponding resistance tensors that appear in the TCAT model. Lastly, we consider the missing pieces from a TCAT formulation of moderate complexity in light of the experimental and computational results reported above.

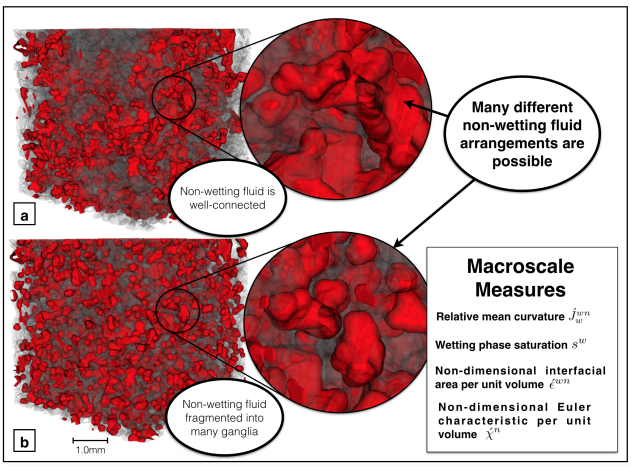

Figure 1: The microscopic arrangement of fluid within rock is responsible for macroscopic differences in capillary pressure. For the configuration shown in (a), the non-wetting fluid (red) is well-connected. When disconnected non-wetting phase is present, the same volume of non-wetting fluid assumes a different distribution within the pore-space, as shown in (b). Many configurations are possible within the complex micro-structure of geologic materials.

References

[1] W. G. Gray and C. T. Miller. *Introduction to the Thermodynamically Constrained Averaging Theory for Porous Medium Systems*. Springer, Switzerland, 2014.