Models of multiphase flow in porous media, including fluid-fluid interfaces

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Abstract:

In many soil and aquifer systems, one encounters simultaneous movements of two or more immiscible fluids. Examples are: moisture transport in the unsaturated zone, artificial recharge of groundwater (downward movement of water in the unsaturated zone), pollution of soil and groundwater by organic liquids, some groundwater remediation methods (e.g. air sparging), and CO_2 sequestration. These systems are modeled using a modified form of Darcy's Law, mass or volume balance equations, and an empirical relationship between capillary pressure and saturation, also known as water retention curve, or soil-water characteristic curve. This empirical relationship for capillarity has been studied extensively in soil physics, subsurface hydrology, and petroleum engineering, because of its central role in multiphase-flow theory. Yet, the standard theory of capillarity effect is a black box with a mostly empirical character. The capillary pressure-saturation relationship is known to be hysteretic (depending on the history of the fluid distribution) and rate-dependent (depending on the rate of flow or rate of change of saturation).

The general understanding is that capillary pressure is equal to the difference in pressures of two fluids. At microscale, this difference is given by the Young-Laplace equation, which prescribes an inverse relationship with the mean radius of curvature. At macroscale, the difference in fluid pressures is assumed to be an algebraic empirical function of saturation, as mentioned above. In this presentation, we revisit these concepts. We will provide a unifying approach to the theory of capillarity based on rational thermodynamics. We present alternative definitions of capillary pressure on both scales. In particular, we make a clear distinction between capillary pressure and pressure difference of fluids. Based on theoretical, experimental, and computational results, we show that the difference in fluid pressures is a function of boundary conditions and dynamic properties of the system, such as flow rate or dynamic viscosities. We propose that the capillary pressure must be an intrinsic property of the fluids-solid system and independent of dynamics of the system. We introduce specific interfacial area (area of fluid-fluid interfaces per unit volume of porous medium) as a new state variable, to account for the fact that capillary pressure is a surface phenomenon and not a volumetric one.

Theoretical, experimental, and computational evidences are presented to show that the empirical capillary pressure-saturation curve should be replaced with the capillary pressure-saturation-interfacial area surface rooted in thermodynamic theory. This surface is uniquely defined and is an intrinsic property of the porous medium. We provide a relationship between fluids pressure difference and capillary pressure, on both micro- and macro-scale. This relationship does depend on the flow conditions and dynamic properties of the system. These concepts are illustrated by data from pore-scale simulations, as well as micro-model and column experiments.

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