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Examination of Capillary Pressure-Saturation-Interfacial Area Relation under Dynamic Conditions using Volume-Of-Fluid (VOF) Method

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Conventional two-phase flow equations (Richards Equation) for porous media at the macroscale require capillary pressure (Pc) and relative permeability (Kr) measured as a function of saturation (S). However, these equations lack solid theoretical foundation, and there is still a considerable gap between the theory and experiments. In typical experiments, an "average"macroscopic capillary pressure is measured as the difference between the pressures of the non-wetting-phase reservoir at the inlet and wetting-phase reservoir at the outlet of a porous medium. Traditionally, this macroscopic phase pressure difference is assumed to be equal to the pore-scale capillary pressure arising due to the curvature of the menisci at the fluid-fluid invasion front. Many theoretical and experimental studies have shown that the macroscopic definition is valid only at equilibrium (i.e. static conditions) and if the phases are connected (Ferrari et al., 2013). Under non-equilibrium (dynamic) conditions, when the fluids are moving, the dynamic capillary pressure measured in experiments is a combination of capillary pressure at the invasion front and the pressure head caused by viscous effects (Lovoll et al., 2011).

The Pc-S relationship is non-unique, and is flow process dependent; different Pc-S curves are defined for drainage and imbibition experiments, resulting in "hysteresis"(Joekar-Niasar and Hassanizadeh, 2012). Gray and Hassanizadeh (1991, 1993) developed a theoretical framework for unsaturated capillary flows which proposed that the inclusion of specific fluid-fluid interfacial area will explicitly define the state of the system, resulting in a unique relation between capillary pressure, saturation and interfacial area (Pc–Sw–awn). In this study, we investigate the capillary pressure–saturation relation under equilibrium and non-equilibrium conditions using pore-scale direct numerical simulations (DNS). Direct numerical simulations (DNS) allow for high resolution description of the geometry and time evolution of interfaces, thereby permitting us to investigate the uniqueness of transient Pc–Sw–awn surfaces.

The porous medium is represented by a quasi-two-dimensional flow network of cylindrical obstructions. Hex-dominant computational grids are generated to accurately resolve the inter-cylinder pore space. The Navier–Stokes (NS) equations are solved in the pore space on an Eulerian mesh using the open-source finite-volume computational fluid dynamics (CFD) code, OpenFOAM. The Volume-of-Fluid (VOF) method is employed to track the evolution of the fluid–fluid interface; a static contact angle is used to account for wall adhesion. Simulations of drainage and imbibition are performed for different capillary numbers by controlling the flow rate of the non-wetting (polydimenthlysiloxane oil) and wetting (water) fluids. From these micro-scale simulations, the pore-scale capillary pressure is directly determined at the fluid-fluid invasion front; this capillary pressure depends on the pore morphology and interfacial energy at the fluid-fluid interface, without accounting for the viscous dissipation which is dependent on system size and invasion speed. The pore-scale capillary pressure is upscaled using the fluid-fluid interfacial area to estimate the macroscopic equilibrium (quasi-static) and non-equilibrium (dynamic) Pc-Sw curves; the Pc–S–awn surface is constructed to determine whether the data points from drainage and imbibition processes fall on a unique surface under transient conditions.

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