SPH Study of Immiscible Flow in Porous Media and the Relation Between Capillary Pressure, Saturation and Interfacial Area

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The classical macroscale approach to modeling two-phase flow of immiscible fluids through porous media is based on a phenomenological extension of Darcy's law and an additional closing equation that relates macroscopic capillary pressure to wetting phase saturation. Hysteretic effects and non-equilibrium contributions are typically lumped into the algebraic capillary pressure-saturation relationship, wherefore correspondings fitting coefficients lack general validity. Contemporary approaches explicitly acknowledge the role of interfacial area in hysteresis, and saturation rate in dynamic capillary pressure [1]. However, these macroscale approaches introduce new balance equations with unknown microstructure-dependent terms yet to be explored. Besides fast x-ray tomography-based experiments, pore-scale direct numerical simulations must be considered a valuable complementary tool for these problems.

Our approach to pore-scale resolved simulations of immiscible, multiphase flow is a weakly compressible SPH method which incorporates the Navier-Stokes equations together with the continuum surface force method to account for the interfacial momentum balances. Attractive features of SPH in this context include its meshfree nature, which makes spatial discretization of complex pore-spaces less computationally expensive as compared to traditional grid or mesh-based methods. Furthermore, the Lagrangian nature, due to which non-linear convective terms are not required to be modeled, thus enhancing stability for locally large Reynolds numbers [2]. The Lagrangian nature of SPH reveals to be particularly useful for multiphase processes since the phase indicator field is intrinsically advected through particle motion and no additional advection equation is required to be considered. The proposed discrete SPH equations are additionally compliant to Galilean invariance and exact mass and linear momentum conservation. In contrast to SPH approaches where the effects of capillarity and interfacial tension are modeled using empirical Lennard-Jones type interaction forces, the present approach is based on the discretization of the governing interfacial mass and momentum balances following [3]. Hence, model calibration routines become unnecessary.

We discuss suitable numerical parameterizations and the predictive capability of the SPH method with respect to immiscible multiphase flow processes in porous media. Subsequently, the aim of our contribution is to discuss the effects of microstructure polydispersity on the equilibrium relationship between capillary pressure, saturation and interfacial area.

References

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