Advanced concepts in two-phase flow in porous media

Nikolaos Karadimitriou, Samaneh Vahid Dastjerdi, and Holger Steeb

Institute of Mechanics (CE), University of Stuttgart, Germany

Two-phase flow in porous media is a process of high significance in many real-life applications, but also from a fundamental science perspective. Such applications are, but not limited to, geological carbon sequestration [1], enhanced oil recovery [2] , and remediation of groundwater/soil contaminated by a non-aqueous phase liquid (NAPL) [3]. Profoundly, the efficient prediction of the evolution of two-phase flow in such applications has an elevated socio-economic impact. The efficiency of this prediction lies with the development of a robust constitutive theory for two-phase flow. In the existing mainstream theories [4, 5], the hysteretic nature of the relationship between capillary pressure and phase saturation, both state variables, cannot be adequately addressed.

To address this inherent disadvantage, by using concepts of volume averaging and rational thermodynamics, Hassanizadeh and Gray [6, 7] developed a macroscale theory for two-phase flow. In this theory, they introduced the interfacial area between the three phases (displacing and displaced fluids and the solid structure) as additional state variables ($P^c = f(a^{ns}, a^{ws}, a^{wn}, s^w)$) . In the same vein, Hilfer and Doster [8] showed that with a phenomenological approach they were able to reproduce experimental findings for capillary pressure and saturation, by differentiating between a percolating and a non-percolating saturation. Even though both proposed theories improved the conceptual consideration of hysteresis, they have been proven to be conditional, both experimentally and numerically [9, 10].

In this work, we aim at experimentally combining the two aforementioned theories of two-phase flow [6, 7, 8]. We put the hypothesis of a potential synthesis of these theories at test, by investigating the role of interfacial area as a separate state variable, while making a clear distinction between connected and disconnected to the reservoir phases (percolating and not). We performed flow-controlled microfluidic experiments, consisting of sequential drainage and imbibition cycles. Subsequently, the images recorded during the experiments were processed and, among other parameters, the interfacial area, the curvature and contact angle of the terminal menisci were extracted. The capillary pressure associated with each wetting/non-wetting interface was calculated and averaged over an REV. Then, a simple, but physically-motivated, function was fitted to the experimental data for phase saturation, capillary pressure, and interfacial area. Our experimental results show that taking the disconnections as a topological measure into account leads to a more efficient modelling of the apparent hysteresis between capillary pressure and saturation, compared to the literature. However, once again, for high capillary numbers, meaning a highly viscous flow regime, this approach seems to break down. We speculate that this can potentially be adequately addressed by taking into account the porous medium geometry, which can be a governing factor as the driving force for extended disconnections. Thus, the inclusion of the Euler number will be investigated in (near) future work.

References

[1] S. Bachu. Sequestration of CO2 in geological media: criteria and approach for site selection in response to climate change. *Energy Conversion and Management*, 41:953–970, 2000.

[2] A. Muggeridge, A. Cockin, K. Webb, H. Frampton, I. Collins, T. Moulds, and P. Salino. Recovery rates, enhanced oil recovery and technological limits. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 372:20120320, 2014.

[3] S. E. Powers, L. M. Abriola, and W. J. Weber. An experimental investigation of nonaqueous phase liquid dissolution in saturated subsurface systems: Steady state mass transfer rates. *Water Resources Research*, 28:2691–2705, 1992.

[4] R. H. Brooks and A. T. Corey. Hydraulic properties of porous media, 1964.

[5] M. Van Genuchten. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils1. *Soil Science Society of America Journal*, 44, 09 1980.

[6] S. M. Hassanizadeh and W. G. Gray. Mechanics and thermodynamics of multiphase flow in porous media including interphase boundaries. *Advances in Water Resources*, 13:169–186, 1990.

[7] S. M. Hassanizadeh and W. G. Gray. Thermodynamic basis of capillary pressure in porous media. *Water Resources Research*, 29:3389–3405, 1993.

[8] R. Hilfer and F. Doster. Percolation as a Basic Concept for Macroscopic Capillarity. *Transport in Porous Media*, 82:507–519, 2010.

[9] N. K. Karadimitriou, S. M. Hassanizadeh, V. Joekar-Niasar, and P. J. Kleingeld. Micromodel study of two-phase flow under transient conditions: Quantifying effects of specific interfacial area. *Water Resources Research*, 50:8125–8140, 2014.

[10] V. Joekar-Niasar, S. M. Hassanizadeh, and A. Leijnse. Insights into the Relationships Among Capillary Pressure, Saturation, Interfacial Area and Relative Permeability Using Pore-Network Modeling. *Transport in Porous Media*, 74:201–219, 2008.