Image-based morphological characterization of multiphase flow in porous media

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The establishment of a physics-based modeling approach for two-phase flow in porous media has been the subject of many research efforts in the last decades. These efforts include the identification of the appropriate state variables to describe and model hysteresis during sequential drainage and imbibition events. Instead of the set of the conventional state variables, such as saturation or effective/residual, trapped, saturation [1, 2, 3], in our experimental work, we include the interfacial area and saturation of only the percolating phase as state variables. To pursue this purpose, while taking benefit of the former attempts, we study a combination of two continuum theories for two-phase flow, as an extended mixture theory-based approach. One theory is the one proposed by Hassanizadeh and Gray [4, 5], which claims that specific interfacial area can be considered as an additional state variable to be considered in effective hysteresis modeling. The other approach was introduced by Hilfer [6, 7], which takes into account the percolating and non-percolating volume fractions for each fluid phase as separate entities. Although each of these continuum theories is only conditionally valid, we show that their combination provides us with a more universal description of two-phase flow in porous media[8, 9].

In our investigations, high-accuracy, time-resolved microfluidic experiments, for various flux boundary conditions, are carried out. We employ optical microscopy to perform cyclic immiscible displacement experiments and record the displacement processes. The recorded images are analyzed with an in-house developed tool. The relevant parameters, such as saturation, capillary pressure, and interfacial area, are extracted from segmented data-sets. Then a simple and thermodynamically-consistent closure equation is chosen and the experimental results are fitted. Through fitting, the existence of a single surface for $P^c - s - a^{wn}$ in all clusters of the fluids in the porous medium is studied, as well as only for the connected-to-the-flow clusters. Comparing the two fits, through R^2 (the coefficient of determination), demonstrates the significance of considering only the percolating saturation of a phase in modeling hysteresis [8].

Another interesting observation is an apparent linear dependency of the specific interfacial area on the saturation assigned to the connected clusters [9]. The good-behaving trend in the data from connected clusters, the increase in the slope of this linear dependency with the number of the events, the reduction in the variability after some events, and the slope difference between drainage events and imbibition displacements are among the results that motivated us to look into this relationship more thoroughly. Further investigating the results, we came across a phenomenon we would like to refer to as the formation of an effective porous medium [10]. After a number of displacement events in all of our experiments (various flow boundary conditions and fluids viscosity ratios in three different porous media), the pores which are invaded during both drainage and imbibition, become repetitive. Thus, a porous medium for both wetting and non-wetting phase forms. The number of events before the effective porous medium forms is different for various flow conditions/porous media. We associate this with how the conditions are in favor of forming disconnected clusters from both phases. The disconnected clusters block some parts of the porous medium for both fluids and result in a new porous domain, which was mentioned above as effective porous medium. The displaced fluids during both drainage and imbibition are shown in Fig. 1.

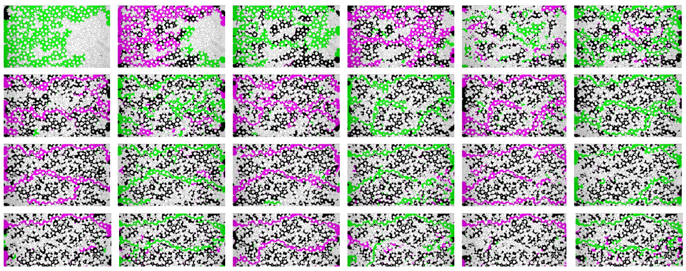

Figure 1: Formation of the preferential paths in a heterogeneous PDMS microfluidic cell. The first image shows primary drainage. Green are drained, and magenta are imbibed pores.

References

[1] Leverett, M.C., 1941. Capillary Behavior in Porous Solids. *Transactions of the AIME* 142:152–169.

[2] Brooks, R. H. and Corey, A. T., 1964. Hydraulic Properties of Porous Media.

[3] Van Genuchten, M., 1980. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal* 44:892–898.

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

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

[6] Hilfer, R., 2006. Capillary pressure, hysteresis and residual saturation in porous media. *Physica A: Statistical Mechanics and its Applications* 359:119-128.

[7] Hilfer, R., 2006. Macroscopic capillarity and hysteresis for flow in porous media. *Physical Review E* 173:016307.

[8] Vahid Dastjerdi, S. and Karadimitriou, N. K. and Hassanizadeh, S. M. and Steeb, H., 2022. Experimental Evaluation of Fluid Connectivity in Two-Phase Flow in Porous Media During Drainage. *Water Resources Research* 58:e2022WR033451.

[9] Vahid Dastjerdi, S. and Karadimitriou, N. K. and Hassanizadeh, S. M. and Steeb, H., 2023. Experimental evaluation of fluid connectivity in two-phase flow in porous media. *Advances in Water Resources* 172:104378.

[10] Vahid Dastjerdi, S. and Karadimitriou, N. K. and Lee, D. and Ruf, M. and Hassanizadeh, S. M. and Steeb, H., 2023. Formation of preferential displacement paths in porous medium. *To be submitted to Geophysical Research Letters*