Comprehensive Study of Fluid-Fluid Displacement in Mixed-Wet Porous Media

Fluid-fluid displacement in porous media occurs in many natural and engineering processes such as water infiltration into soil, geological carbon dioxide storage, and enhanced oil recovery. It has long been recognized that wettability plays an important role in the displacement process. For instance, the displacement pattern of a viscous ambient fluid by a less viscous invading fluid becomes more compact as the invading fluid becomes more wetting to the porous medium. Thanks to decades of research, we now have a fairly good understanding of fluid-fluid displacement in porous media with uniform wettabilities. In contrast, our knowledge of fluid-fluid displacement in porous media with heterogeneous wettabilities (i.e., mixed-wet) is much less complete, even though mixed-wet conditions are common in many subsurface processes.

Here, we study the fluid-fluid displacement pattern in porous media with spatially heterogeneous wettabilities. Experimentally, we perform constant-rate displacement of a viscous ambient fluid by a less viscous invading fluid in microfluidic flow cells patterned with vertical posts. Our microfluidic flow cells are made of a UV-sensitive photo-curable polymer whose surface energy can be locally tuned by exposure to high-energy UV light. These microfluidic flow cells let us achieve clusters of posts that are distinctly more wetting to the invading fluid than the rest of the flow cell. We image the experiment at high resolution, providing simultaneous visualization of both the physics of wetting at the pore scale and the impact of wetting on the macroscopic displacement pattern. These experiments show the preferential filling of the mixed-wet pores when the hydrophilic post is weakly hydrophilic, whereas the invading fluid fully saturates the hydrophilic clusters when the hydrophilic post is more strongly hydrophilic. Numerically, we study the quasi-static evolution of a meniscus through a mixed-wet pore throat and simulate the experiments by using a novel pore network model. We achieve excellent agreement between the pore network model results and the experiments. Finally, we apply the pore network model to explore the impact of cluster size, correlation and distribution, and wettability contrast on the displacement pattern. Our work presents a fascinating and complex phase diagram of fluid-fluid displacement in mixed-wet porous media.