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Imaged-based Study of Fluid Droplet Deformation During Immiscible Ferrofluid Flooding

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Ferrofluid, a stable suspension of superparamagnetic nanoparticles in a liquid carrier, can be manipulated. In an external magnetic field, either constant or evolving, magnetic forces drives the ferrofluid to deform and move, leading to the deformation of the fluid-ferrofluid interface. This has been extensively used in microelectromechanical systems (MEMS) and here we are motivated to extended these studies to subsurface porous media application, including enhanced oil recovery and environmental remediation. Unlike MEMS devices where non-wetting or non-aqueous phase liquid (NAPL) droplets are typically the ferrofluid to be deformed and manipulated, this is not possible for subsurface applications: oil or NAPL are to be recovered and only aqueous phase could be the ferrofluid. Incidentally, the high-resolution imaging of wetting ferrofluid / non-wetting fluid displacement are very limited.

A converging-diverging single channel glass micromodel with varying depth was fabricated using a standard lithography procedure. The single channel was initially saturated with brine, and then saturated with a mixture of decane and mineral oil. The micromodel was then flooded using a water-based ferrofluid under a microscope for 47 hours until no noticeable movement of remaining oil droplet was observed and the system was assumed a steady-state. Then, a magnetic field a) transverse to the flow direction and b) rotating magnetic field were applied to the system in separate experiments.

The magnetic field caused oil droplet deformation (specifically, elongation along the magnetic field direction), and dynamic breakup into smaller droplets and subsequent residual oil saturation reduction in a rotating magnetic field. In addition to studying saturation differences, we quantify the curvature of several oil droplets where the resolutions allows before and after the magnetic field application. We finally focus on experiments in a Hele-Shaw cell without flooding, where we observe self-assembly of oil droplets, the formation of the hydrophilic magnetic nanoparticle microstructures (chains under the magnetic field) and their interaction with the oil blobs.

The experimental results show that, during a ferrofluid flooding, in the case of multiple residual fluid droplets within a pore, the fluid droplets can be deformed and potentially controlled using an external magnetic field. Such deformation by the magnetic force can aid or obscure the mobilization of the fluid droplets and has a potential to control the trapped oil saturation near the wellbore in enhanced oil recovery, and to control fluids in MEMS.

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