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Editorial: Nonequilibrium multiphase and reactive flows in porous and granular materials

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Editorial on the Research Topic
Nonequilibrium multiphase and reactive flows in porous and granular materials

Porous systems that involve the flow of multiple fluids, particles, or solutes, capable of undergoing reactions with each other or with the solid porous matrix, often exist in an out-of-equilibrium state. These systems are driven away from equilibrium by various underlying mechanisms. These mechanisms include interfacial instabilities caused by capillary or viscous forces, as well as physical alteration of the pore space through mechanical or chemical processes like fracturing, compaction, precipitation, and dissolution. An inherent feature of many porous and granular systems is their multiscale heterogeneity. An extreme example is in geosciences, where heterogeneity and mechanisms at the microscopic scales (e.g., in nanometer-sized pores) could strongly affect the behavior at the field scale (km-sized reservoirs). The multiscale, nonequilibrium nature of these systems is manifested by the emergence of complex, preferential flow patterns and dependencies on the path (hysteresis) and rate of external driving forces. Modeling, understanding, predicting, and even controlling the evolution of the flow and deformation in these systems is a substantial scientific challenge across disciplines including engineering, physics, geosciences and mathematics and plays a crucial role in multiple practical applications.

The papers included in this Research Topic explore some of the fascinating problems which form the wide interdisciplinary field of nonequilibrium flows in porous and granular materials. Particular focus was given to the impact of various microscopic mechanisms on two-fluid displacement patterns. In two articles by Lan et al. and Fyhn et al., pore network simulations were used to explore the link between the *microscopic* (pore-scale) filling mechanisms and their alteration by changing the wettability (the relative affinity of the fluids to the solid surface), and the resulting *macroscopic* (sample scale) invasion patterns. Lan et al. focused on the interplay between pore geometry and wettability, two properties that can vary considerably among different types of porous materials and substantially affect fluid-fluid displacement. The authors show that the displacement stability could be controlled by engineering the pore geometry to have a gradient in pore sizes, and that the effect of this microstructure can be reversed depending on the wettability (contact angle). Fyhn et al. reveal an interesting flow regime in which connected paths with zero capillary forces span the length of a porous network, thus eliminating the need for a minimum threshold pressure to initiate flow. This regime, observed in systems formed by grains having different wetting properties, transitions to power-law relationships with varying pressure drops, offering valuable insights into the rheological behavior of such systems.

Meisenheimer and Wildenschild studied experimentally the topology of interfaces formed by internal generation of gas bubbles in the liquid phase, of relevance to various natural and industrial settings, for instance, methane venting in water-saturated sediments or air sparging for pollution remediation. The authors used X-ray micro-CT to both generate air bubbles and to characterize the fluid-fluid interface in 3D porous media (bead pack). Good agreement was found between the experimental data and geometric state functions describing the interfacial area, mean curvature and the Euler characteristics (a measure of phase connectivity).

The interplay between gravity and viscosity and its effect on two-fluid displacements was studied experimentally by Brodin et al. The authors injected a heavier, more viscous fluid into a porous sample saturated with a lighter, less viscous fluid and observed the 3D invasion patterns using a table-top 3D scanner based on optical index matching and laser-induced fluorescence (a simpler and cheaper alternative to X-ray or magnetic resonance). A stability criterion was developed to reflect the balance between the (stabilizing) viscous and (destabilizing) gravitational forces.

The work by Jung et al. examined the role played by viscoelasticity on fluid displacement and trapping in porous media. Microfluidics experiments, designed to elucidate the effects of the rheology of viscoelastic fluids, were used to show how purely elastic instabilities could be responsible for an improved mobilization of capillary entrapments. Viscoelastic fluids were also studied theoretically by Sudarmozhi et al. The authors studied the steady-state magnetohydrodynamic flow of Maxwell fluids through a porous flat plate, including the effect of heat and thermal radiation. The system of differential equations was solved numerically to quantify the combined impacts of heat generation, mass diffusion and thermal radiation over the porous plate in terms of the governing dimensionless groups.

Finally, Hayashi studied precipitation reactions involving diffusing chemical species, focusing on the resulting banded patterns (so-called "Liesegang rings"). The author exposed a new type of Liesegang-like pattern, where Fe_2^+ and OH^- ions are first produced at opposing anode and cathode respectively, and, partly driven by an imposed electric field, the ions diffuse through a gel toward each other, to precipitate $Fe(OH)^3$. Striking periodic bands were observed when the samples were subjected to cyclic alternating voltages, with the banding patterns strongly influenced by applied voltage levels and periods, the number of cycles and the length of the gel column.

In summary, the articles in this Research Topic demonstrate the intricacy of nonequilibrium processes in porous and granular materials and some of the experimental, theoretical and numerical challenges that must be overcome to obtain quantitative understanding and physically-based models.

Author contributions

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Conflict of interest

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