PhD Thesis Title

Interfacial instability in porous medium flow: Influencing factors of viscous fingering

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Abstract

The immiscible and miscible fluid–fluid displacement in porous media is of great importance in several scientific and engineering applications, such as enhanced oil recovery (EOR) and CO2 geo-sequestration. When a low viscosity fluid replaces a high viscosity fluid in porous media, an interfacial instability occurs known as viscous fingering, also known as Saffman-Taylor instability, which reduces the efficiency of the displacement process. Numerous investigations have been conducted to stabilize and control the viscous fingering phenomenon in both immiscible and miscible displacement, the majority of these studies have considered Newtonian fluid. However, due to the complex behavior of non-Newtonian fluids, studies on interfacial instability considering non-Newtonian fluids are still being explored. In this thesis, viscous fingering instability problem is studied considering the non-Newtonian fluid displacement. We present the study of viscous fingering in a radial Hele-Shaw cell in shear-dependent rheological fluid, which transitions from the Newtonian to shear thinning behavior at low shear rates for different constant flow rates of the injection fluid and gap thickness. The viscous fingering characteristics such as side branching, growth of second-generation fingers, and inhibition of tip splitting are observed in the case of shear-thinning flow regime, both experimentally and numerically. The stability of the fingering at ultra-low flow rates exists much beyond that predicted by linear stability analysis. We propose a quantitative criterion from the linear stability analysis involving non-Newtonian (shear-thinning fluid) to control the pattern formation and suppress viscous fingering controlling a parameter, which is a function of the physical and operating conditions. It is possible to stabilize the interface following a non-linear injection rate, $Q \sim t^{-(2-n)/(2+n)}$, which is related to the displaced fluid rheology (n : power-law index). Furthermore, we have experimentally shown a feasible approach toward long-term fingering stabilization with the continuous cyclic time-dependent injection flow rate. We experimentally investigate the interplay and transition of viscous fingering and fracturing for a shear-thickening fluid. We have used cornstarch suspension of different compositions and the rheology of the suspension exhibits shear thickening behavior beyond a critical shear rate. The evolution from viscous fingering to dendritic fracturing morphology is observed. The displacement efficiency of the process can be computed based on the fraction of injected phase to displaced phase as a function of injected volume for different weight fractions of cornstarch suspension. The viscous fingering pattern in 2D media can be significantly different from the 3D pattern as it depends on the geometrical arrangements of the granular structure and flow connectivity in the pore network. However, fingering patterns in the three-dimensional (3D) scenario is different than the 2D case, on account of the gravitational segregation being more effective in 3D porous media. The displacement of the denser fluid by the less dense fluid creates a gravitational tongue, inducing a non-uniform interface that diminishes the displacement efficiency. The interaction between viscous fingering and gravitational segregation is observed in different fields, including hydrocarbons recovery, carbon-dioxide (CO2) sequestration, saltwater aquifer intrusion, and groundwater pollution. We study the three-dimensional viscous fingering morphology to investigate the effect of fluid miscibility and porous medium permeability using the X-ray micro-computed tomography (micro CT) technology. The phase miscibility of the injection fluid to the displaced fluid affects the fingering phenomena, transitioning from dispersion limited to diffusion. The areal sweep efficiency for miscible flow is high in comparison of immiscible flow. We have used the fractal analysis to analyse the complex patterns, and the fractal dimension is related to the process conditions. We report 3D diffusion-limited aggregation simulations to obtain patterns similar to the miscible fingering patterns and provide insights into the pattern growth behavior. The multiphase flow during the steam as well as CO_2 injection EOR method can affect the viscous fingering. The coexistence of vapor and liquid in the displacing phase induces anisotropy and heterogeneity in the viscous fingering pattern, markedly distinctive from the classical observations in Hele-Shaw cell experiments and exhibits non-intuitive pattern formations. Therefore, the experimental investigation focuses on immiscible displacement within a radial Hele-Shaw cell using a phase-changing medium. The high viscosity oil is displaced by low viscosity methanol vapor, along with its condensate at different injection pressure. The thermal front movement is impeded due to heat transfer between the fluids as well as the large time scale of thermal diffusion to the other side of the observation window (quartz glass), causing the thermal front to lag behind the fluid front. Initially, momentum diffusion governs heat transfer, followed by thermal diffusion dominance. Interfacial oscillations induced by the Marangoni effect stemming from temperature-induced interfacial tension gradients are observed. Overall, the thesis objective is based on understanding and proposing engineering interventions to the complex problem of interfacial instability in the context of enhanced oil recovery technology.

Keywords: Viscous fingering; Enhanced oil recovery (EOR); Radial Hele-Shaw cell; Saffman-Taylor instability; Non-Newtonian Fluid; Linear stability analysis; fracturing; Fractal dimension; Immiscible and miscible displacement; 3D viscous fingering; X-ray micro-computed tomography; Porous media flow; Diffusion-limited aggregation; Multiphase fluid flow