Studies on Miscible Viscous Fingering in Polymeric and Nanofluids

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Abstract

The flow displacement process, typically through microchannel or porous media, suffers from fingering phenomenon which manifests in the form of finger-like patterns around the interface region. The viscous fingering is a hydrodynamic instability, also known as Saffman-Taylor instability, and is attributed to the viscosity stratification between the displacing and displaced fluids. Modulation of classical viscous fingering patterns by incorporating nanoparticles and polymers into the fluids has generated a strong interest as incorporation of a small amount of these additives results into phenomenal alteration in fluid properties. The first part of the present study addresses the role of nanofluids in the onset and growth kinetics of fingering using linear stability analysis and full numerical simulations. The linear stability analysis constructs the dispersion curves indicating linear growth-rate of fingers as a function of wavenumber. Numerical simulations reveal the later-stage non-linear dynamics of fingers providing insight into the severity of viscous fingering phenomena. The effect of viscosity enhancement due to particle loading and concentration-dependent particle diffusivity on fingers formation is examined and the findings are correlated to the nature of viscosity profiles in the flow domain.

Further, the influence of polymeric chains on finger formation is investigated using the linear stability analysis, the full numerical simulation as well as performing experiments. Polymeric solutions in general exhibit various non-Newtonian features, such as shear-rate dependent viscosity, elasticity, and yield-stress. The dynamics of viscous fingering is therefore strongly influenced by the nonlinear rheology of the polymeric fluids. Two different scenarios of polymer incorporation are examined when either the displacing or displaced fluid is a polymeric fluid. First, the polymeric solutions are considered to exhibit shear-thinning viscosity as well as elasticity but no yield-stress, and are rheologically described using the White-Metzner model. The role of shear-thinning behaviour and fluid elasticity in the fingering dynamics is examined by performing linear stability analysis and numerical simulations. The study reveals that for similar linear viscoelasticity, introducing shear-thinning behaviour into the displaced (displacing) fluid leads to suppressed (enhanced) fingering patterns, primarily due to modification of the gap-averaged viscosity. For a fixed ratio of effective viscosities of two fluids under flow conditions, the shear-thinning behaviour

tends to enhance the fingering growth regardless of the flow arrangement. Thus, the study suggests that in addition to the viscosity modification, the nature of entire flow curve (meaning nonlinear rheology) plays an important role in fingering dynamics. The interplay between the viscosity contrast and the complete rheological description of the fluid governs the onset as well as the non-linear evolution of finger formation. For similar viscous behaviour of polymeric fluids, introducing elastic behavior to either of the two fluids tends to not only attenuate the fingering growth rate but also alter the structure of fingering in the nonlinear regime. The role of yield-stress fluids, described by Bingham model, is examined in a separate problem. Similar to the shear-thinning behaviour, for fixed effective viscosity contrast, presence of yield-stress always intensifies the fingering growth, irrespective of the flow arrangement.

The viscous fingering in polymeric fluids is also examined by performing flow visualization experiments in Hele-Shaw cell. Polyethylene-oxide (PEO) solutions of different concentration and molecular weights are used for polymeric fluids. The study shows that the development of fingering patterns in polymeric solutions is more complex vis-a-vis Newtonian fluid, exhibiting ` branched fingers with tip-splitting even for the similar effective viscosity contrast and regardless of the flow arrangement. Particularly, flow displacement of either high concentration or high molecular weight PEO solution exhibits fractal-like growth. The additional non-linear behavior, side-branching, tip-splitting, and shielding, is attributed to the inhomogeneity in fluid viscosity due to local flow behaviour and normal stresses (or elasticity). Finally, as a way to alter the viscous fingering, the flow displacement in which the two fluids are reactive and produce nanoparticle in the diffusive zone, is considered. The role of nanoparticles diffusivity is analyzed with the help of numerical simulations. The effect of concentration-dependent particle diffusivity and anisotropic diffusion on fingering growth is examined. The concentration-dependant diffusivity is found to have a destabilizing effect on the flow displacement. Concentration-dependent diffusivity leads to stronger viscosity gradients in the vicinity of the interface, hence intensifies the fingering growth. Overall, a comprehensive understanding of viscous fingering dynamics enables one to design an efficient flow displacement process.