Direct Numerical Simulation of Immiscible Two-phase Flow in Rough Fractures from Viscous to Capillary Fingering – Impact of Flow regime and Structure of the Aperture Field

Insa Neuweiler¹, Rahul Krishna¹, Zhibing Yang², and Méheust Yves³
¹Leibniz Universität Hannover, Institute of Fluid Mechanics, Department of Civil Engineering / Inst. of Fluid Mechanics, Hannover, Germany
²Wuhan University, State Key Laboratory of Water Resources Engineering and Management, Wuhan, China
³University of Rennes, Géosciences Rennes, Rennes, France

Immiscible fluid displacement in rough geological fractures plays a crucial role in various subsurface processes, such as enhanced oil recovery and geological carbon sequestration. In horizontal settings, this displacement is governed by capillary and viscous forces, resulting in the emergence of various displacement patterns as a less viscous fluid displaces a more viscous one (drainage). The macroscopic variables quantifying the flow process differ substantially between the two limit unstable regimes, namely capillary and viscous fingering, for very low and very large capillary numbers, respectively. While there has been extensive investigation of such phenomena in the context of porous media, studies on rough fractures are relatively scarce. In this study, we perform Direct Numerical Simulation (DNS) to analyze the process of drainage by solving the Navier–Stokes equations within the fracture pore space, employing the Volume of Fluid (VOF) method to track the evolution of the fluid-fluid interface. We consider a wide range of Capillary numbers ($10^{-5}$ – $10^{-2}$) encompassing both the viscous and capillary dominated regimes, as well as three distinct viscosity ratios (0.8, 0.05 and 0.01), and address realistic synthetic fracture geometries characterized by their Hurst exponent, the ratio of the roughness amplitude to the mean aperture (denoted as the fracture closure), and the correlation scale $L_c$ (i.e., the scale above which the two fracture walls are identical) of the investigated fracture domain. The fracture closure is varied between 0.1 and 1, and $L_c$ between $L/32$ (aperture field with spatial correlations only at small scales) and $L$ (self-affine aperture field), where $L$ denotes the length of the domain. Starting from the invasion morphologies of the fluid-fluid interface, we examine various pore-scale and macroscopic flow observables, allowing us to systematically characterize the displacement processes of the two-phase system at the hydrodynamic scale. Additionally, flow observables, such as the residual saturation of the displaced fluid and the interfacial area, can be utilized to define the parameter functions of a continuum scale two-phase flow model towards upscaling.