Partitioning dynamics of unsaturated flows in fractured porous media: Laboratory studies and three-dimensional multi-scale smoothed particle hydrodynamics simulations of gravity-driven flow in fractures

Kordilla, J., Shigorina E., Noffz, T., Bresinsky, L., Dentz, M., Sauter M., Tartakovsky A.

Preferential flow dynamics in unsaturated fractures remain a challenging topic on various scales. On pore- and fracture-scales the highly erratic gravity-driven flow dynamics often provoke a strong deviation from classical volume-effective approaches. Against the common notion that flow in fractures (or macropores) can only occur under equilibrium conditions, i.e., if the surrounding porous matrix is fully saturated and capillary pressures are high enough to allow filling of the fracture void space, arrival times suggest the existence of rapid preferential flow along fractures, fracture networks, and fault zones, even if the matrix is not fully saturated.

Modeling such flows requires efficient numerical techniques to cover various flow-relevant physics, such as surface tension, static and dynamic contact angles, free-surface (multi-phase) interface dynamics, and formation of singularities in the case of merging or snapping flow modes (droplets, rivulets). Here we demonstrate the importance of such flow modes on the partitioning dynamics at simple fracture intersections, with a combination of laboratory experiments, analytical solutions and numerical simulations using our newly developed massively parallel smoothed particle hydrodynamics (SPH) code.

We show that flow modes heavily influence the "bypass" behavior of water flowing along a fracture junction. Flows favoring the formation of droplets exhibit a much stronger bypass capacity compared to rivulet flows, where nearly the whole fluid mass is initially stored within the horizontal fracture. This behavior is demonstrated for a multi-inlet laboratory setup where the inlet-specific flow rate is chosen so that either a droplet or rivulet flow persists. The effect of fluid buffering within the horizontal fracture is presented in terms of dimensionless fracture inflow so that characteristic scaling regimes can be recovered. For both cases (rivulets and droplets), flow within the horizontal fracture transitions into a Washburn regime until a critical threshold is reached and the bypass efficiency increases. For rivulet flows, the initial filling of the horizontal fracture is described by classical plug flow. Meanwhile, for droplet flows, a size-dependent partitioning behavior is observed, and the filling of the fracture takes longer. For the case of rivulet flow, we provide an analytical solution that demonstrates the existence of classical Washburn flow within the horizontal fracture.

Furthermore we provide insights into the coupling of fracture flow and classical Richards-based flow in the adjacent porous matrix with our new multi-scale SPH code currently in development.