Geophysical Research Abstracts
Vol. 19, EGU2017-16498-3, 2017
EGU General Assembly 2017

Free-Surface flow dynamics and its effect on travel time distribution in unsaturated fractured zones - findings from analogue percolation experiments

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Flow in unsaturated fracture networks constitutes a high potential for rapid mass transport and can therefore possibly contributes to the vulnerability of aquifer systems. Numerical models are generally used to predict flow and transport and have to reproduce various complex effects of gravity-driven flow dynamics. However, many classical volume-effective modelling approaches often do not grasp the non-linear free surface flow dynamics and partitioning behaviour at fracture intersections in unsaturated fracture networks. Better process understanding can be obtained by laboratory experiments, that isolate single aspects of the mass partitioning process, which influence travel time distributions and allow possible cross-scale applications.

We present a series of percolation experiments investigating partitioning dynamics of unsaturated multiphase flow at an individual horizontal fracture intersection. A high precision multichannel dispenser is used to establish gravity-driven free surface flow on a smooth and vertical PMMA (poly(methyl methacrylate)) surface at rates ranging from 1.5 to 4.5 mL/min to obtain various flow modes (droplets; rivulets). Cubes with dimensions 20 x 20 x 20 cm are used to create a set of simple geometries. A digital balance provides continuous real-time cumulative mass bypassing the network. The influence of variable flow rate, atmospheric pressure and temperature on the stability of flow modes is shown in single-inlet experiments. Droplet and rivulet flow are delineated and a transition zone exhibiting mixed flow modes can be determined. Furthermore, multi-inlet setups with constant total inflow rates are used to reduce variance and the effect of erratic free-surface flow dynamics. Investigated parameters include: variable aperture widths df, horizontal offsets dv of the vertical fracture surface and alternating injection methods for both droplet and rivulet flow. Repetitive structures with several horizontal fractures extend arrival times but also complexity and variance. Finally, impacts of variable geometric features and flow modes on partitioning dynamics are highlighted by normalized fracture inflow rates. For higher flow rates, i.e. rivulet flows dominates, the effectiveness of filling horizontal fractures strongly increases. We demonstrate that the filling can be described by plug flow, which transitions into a Washburn-type flow at later times, and derive an analytical solution for the case of rivulet flows. Droplet flow dominated flow experiments exhibit a high bypass efficiency, which cannot be described by plug-flow, however, they also transition into a Washburn stage.