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Modeling averaged displacement fronts in heterogeneous media with multirate mass transfer models

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The morphology of fluid-fluid interfaces during immiscible displacement has been studied intensely on length scales where the pore space is resolved. Depending on the dimensionless numbers of the flow process, the front morphology can be different: compact or irregular with different cluster distributions of trapped displaced fluid. There are also flow regimes with a cross-over from a compact displacing fluid far away from the front and irregular fluid distribution at the front.

If displacement is considered on larger length scales, the pore space and fluid-fluid interfaces can no longer be resolved. The front is in this case rather described by an isoline of the displacing fluid saturation. Displacement fronts on large length scales in heterogeneous media can also show complex front morphology: compact or irregular with fluid clusters of displaced fluid that are trapped behind the front. As displaced fluid may also be immobilized (meaning it is not trapped, but it is surrounded by displacing fluid, so that the surrounding material has a very low permeability) and is in this case displaced only very slowly, one also finds a cross-over regime with a compact region far away from the front and an irregular front. The morphology is influenced by the interplay of heterogeneous structure and the stability of the displacement process.

We focus on displacement scenarios with crossover from irregular fluid distribution around the front due to immobilized fluid that is eventually displaced to compact far behind the front. To have a quantification of the front morphology is important, for example, to estimate mass transfer of given components between the fluids. We study the front morphology using numerical simulations of displacement processes in porous media composed of two different materials. We consider different heterogeneous structures. We consider flow scenarios with different capillary number and viscosity ratio of the fluids. It is demonstrated that the connectivity of the heterogeneous structure has a crucial influence on the front morphology.

For these numerical simulations we compare the averaged fluid distribution to an upscaled one-dimensional model. In the upscaled model, the immobilization of displaced fluid behind the front is captured by a double continuum approach, where the immobilized fluid is considered an immobile continuum. The size of the immobile continuum changes with time. The flow is modeled in the mobile continuum with a multi-rate mass-transfer term to capture exchange with the immobile domain. The rate coefficients for the mass transfer have to be estimated from the size distribution of immobilized fluid clusters. It is demonstrated that such a simplified model can describe the displacement well, if the front morphology is not too complex.