Pore-scale Modeling of Immiscible Two-phase Flow in Predominantly 2D Microfluidic Porous Domains

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Abstract

Immiscible two-phase flow in porous materials is a process of significant scientific and applied interest encountered in numerous technological applications related to energy and the environment (e.g. subsurface water flows, petroleum recovery, soil remediation and geologic carbon dioxide storage). Unlike processes that include only single phase flow, which are typically approximated at the REV-scale using Darcy's law (thus exhibiting a linear dependence between flow rates and the applied pressure difference), in two-phase flows the combined effects of viscous, capillary and gravity forces within the heterogeneous/tortuous pore space render a highly non-linear flow problem. As such, immiscible flow processes within porous materials can be efficiently treated using novel pore-scale numerical approaches, that furthermore provide the potential for upscaling the results for use in the context of field-scale simulators.
In this contribution, we study the dynamics of immiscible two-phase flow in a microfluidic porous domain that consists of randomly distributed circular obstacles to "mimic" the tortuous nature of actual porous materials. We employ COMSOL's coupled implementation of the level set method and the laminar Navier-Stokes equations (in the Stokes limit) in order to track interface movements through the domain over an extended region of capillary numbers, where either viscous or capillary forces are dominant. Depending on the capillary number and the viscosity ratio of the fluids, we recover a rich diagram of phase distribution patterns despite the small/finite dimensions of the computational domain. Our numerical results are then compared against an experimental study of immiscible flow in identical microfluidic structures performed by the Environmental Hydrogeology group of Utrecht University in order to demonstrate the predictive capabilities (and limitations) of the level-set method for the numerical modeling of immiscible flows at the pore-scale.

Figures used in the abstract

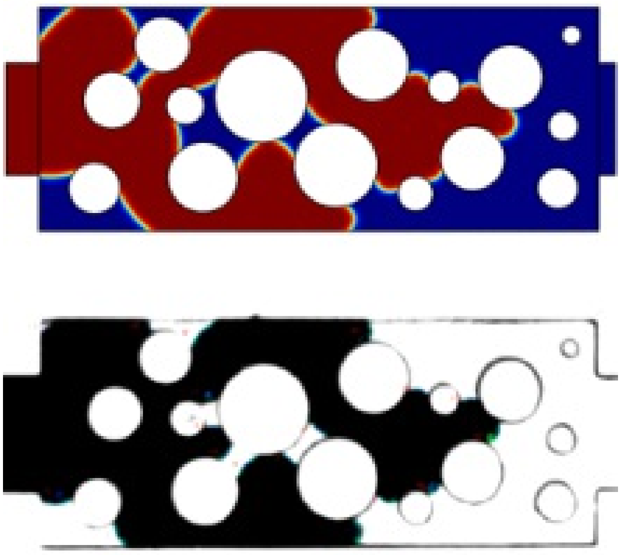

Figure 1: Comparison of experimental (bottom) and numerical (top) phase distribution patterns obtained during the immiscible displacement of Fluorinert by water within a PDMS microfluidic chip 2.5mm x 1.0mm in size and depth 0.1mm. Died water is injected from a channel with 0.5mm x 0.1mm cross-section on the left at constant pressure 1860Pa and recovered from a similar channel on the right side of the chip.