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Direct numerical simulation of the two-phase flow in a pore network and comparative analysis with drainage/imbibition tests on glass micromodels

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The experimental and numerical study of drainage and primary/secondary imbibition cycles of immiscible displacement are crucial for several practical applications such as the spreading of oil pollutants in soils and groundwater, the in-situ remediation by water flushing, and the enhanced oil recovery (EOR) from reservoir rocks. In order to simulate two-phase flow in pore networks, by now, most attention has been paid on mechanistic pore network models (PNM) and Lattice Boltzman (LB) approaches. The prediction of the two-phase flow pattern with direct numerical simulation, though computationally cumbersome, is a challenge. To address such a challenge, several numerical approaches are available, like the level set method, where issues such as maintaining a zero net mass balance equation remain unresolved [1]. In this context, a phase field approach [2] is used to model the immiscible displacement of two fluids within the pore network of a specific micromodel [3]. Central to this approach is the Cahn-Hilliard fourth-order partial differential equation, governing the dynamics of the chemical potential (G) and mobility (γ). These parameters are intrinsically linked to key physical factors such as interphase thickness (ε), capillary width, mixing energy (λ), and surface tension coefficient (σ), Eqs. (1)-(3)

(1)∂φ/∂t+u∇φ=∇γ∇G

(2)G=-λ[∇^2 φ+(φ(φ^2-1))/ε^2]

(3)σ=(2√2)/3 λ/ε

The pore network is reconstructed from an actual glass-etched micromodel, for which extensive experimental data are available for validation and comparative analysis. This reconstruction is based on the software developed by the OpenPNM team [4], and the resulting geometry is then integrated into the Comsol Multiphysics® commercial software for simulation. In the numerical model, the Cahn-Hilliard equation is utilized to predict phase distribution under varying values of viscosity ratio, κ (=μinjected/μdisplaced), Reynolds number, and Capillary number. For mesh generation within the micromodel, approximately 2 million are used for network width W=10.1 cm and length L=15.3 cm. Depending on the initial conditions set, each simulation in this time-dependent model runs for a duration of 7 to 12 hrs.

To evaluate the model validation, the numerical results are compared with corresponding experiments of drainage/imbibition cycles, performed under varying fluid properties and flow conditions [5]. Special attention is paid on the potential to predict numerically the visualized flow pattern and the measured transient response of the pressure drop, when the oil phase in drainage or the aqueous phase in secondary imbibition are non-Newtonian shear-thinning fluids, by accounting for the actual fluid rheology. During the drainage stage, there is a notable agreement between the experiment and the numerical model. Discrepancies, minor in nature and within a 20% deviation, can be attributed to the idealized structure inherent in numerical simulations. Additionally, the consistency between 3D and 2D model outcomes suggests that a two-dimensional representation adequately captures the complexities of the problem without significant loss of information.

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