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Depth-integrated model of immiscible two-phase flow in open rough fractures

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Immiscible two-phase flows in geological fractures are relevant to various industrial contexts, including subsurface fluid storage and hydrocarbon recovery. Direct numerical simulations (DNS) of first-principle equations, which resolve three-dimensional (3-D) fluid-fluid interfaces, can address various flow regimes but are computationally intensive. To retain most of their advantages while reducing the computational cost, we propose a novel two-dimensional (2-D) approach based on depth-integrating the 3-D first principle equations over the local fracture aperture. Such existing models have, so far, been restricted to single-phase permanent flow in rough fractures **[1,2]** and two-phase flow in 2-D porous media **[3]**. Considering a description of two-phase flow relying on the Navier-Stokes equations coupled with the volume-of-fluid method for interface capturing, we derive a depth-integrated model based on the lubrication approximation and assuming a parabolic out-of-plane velocity profile. Wall friction and out-of-plane capillary pressure are incorporated as additional terms in the 2-D momentum equation. The model then relies on a geometric description reduced to the fracture's aperture field and mean topography field. Implemented in OpenFOAM, it is validated against experimental **[4]** and 3-D DNS simulation results **[5]** for viscous fingering in a Hele-Shaw cell, and subsequently applied to a synthetic geological fracture geometry over a wide range of capillary numbers (Ca). With a tenfold reduction in computational cost compared to 3-D DNS, the model accurately predicts key flow metrics, such as macroscopic pressure drops and various statistical observables of the fluid displacement morphologies. The 2-D model performs best at intermediate Ca, demonstrating a potential for bridging hydrodynamic and continuum-scale models.

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References

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