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Pore-scale investigation of forced imbibition in natural rocks through interface curvature and pore topology analysis

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Forced imbibition, which involves the invasion of a wetting fluid in natural rocks, plays an important role in efficient development of hydrocarbon resources and geological storage of carbon dioxide. However, the interface dynamics influenced by complex topology lead to non-wetting fluid trapping, particularly the underlying mechanisms under viscously unfavorable conditions remain unclear. This work reconstructs digital rocks of sandstone to simulate forced imbibition by direct numerical simulation methods. The interface dynamics and fluid-fluid interactions are investigated through transient simulations, while the pore topology metrics are introduced to analyze the impact on steady-state residual fluid distribution obtained by a pseudo-transient scheme. Results show that the cooperative pore-filling process promoted by corner flow is dominant at low capillary numbers; the inlet pressure, mass flow, and interface curvature are unstable, corresponding to complicated interface dynamics and higher residual fluid saturation. The interface curvature gradually increases during forced imbibition, with the pore-filling mechanisms involving the cooperation of main terminal meniscus movement and arc menisci filling. Complex topology with small diameter pores may induce instability of interface curvature. Residual fluid saturation is negatively correlated with porosity and pore throat radius, and positively correlated with tortuosity and the aspect ratio associated with pore throat radius. A large mean coordination number characterizing global connectivity promotes imbibition. While the high connectivity characterized by standardized Euler number corresponding to small pores has a high probability of non-wetting fluid trapping.

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