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Fracture regulates statistical steady-state Rayleigh-Darcy convection pattern in porous media

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When concentration or temperature contrast results in higher fluid density at the top of a porous stratum than that at the bottom of a porous stratum, buoyancy may drive Rayleigh-Darcy (R-D) convection that fundamentally shapes the transport and reactive dynamics. R-D convection commonly emerges in CO2 sequestration and in stratums with high geothermal gradient. Regardless of numerous studies on flow pattern and transport kinetic model in homogeneous media, the effect of heterogeneity (especially the emergence of fractures) on R-D convection is largely under debate.
Here, we study how a single vertical fracture shapes the flow field during R-D convection at steady-state. We adopt Lattice Boltzmann modeling method with two coupled Lattice Bhatnagar-Gross-Krook (LBGK) models. We vary Rayleigh number (characteristic ratio of gravitational-driven flow flux over molecular diffusion flux) from 500 to 6000, fracture volume fraction from 6.25% to 23.86%, and fracture-matrix permeability ratio from 1.01 to 451. Flow patterns are recorded with the system falls to statistical steady state.
Surprisingly, most numerical simulations show consistent pattern: high-density fluid mainly flows down through the fracture, whereas the low-density fluids go upward through the matrix. We propose a simple theory that the flow pattern is determined by minimization of total gravitational potential energy leads to this flow pattern. We establish a toy theoretical criterion, that well predicts the flow pattern calculated from numerical simulation. This criterion can be extended to other heterogeneous media than fractured media.
This successful and theoretical approach on simple system demonstrates how geometrical heterogeneity reduces fluid flow uncertainty. In the future, we will investigate heat & mass transport during R-D convection in more complicated systems.

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References

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