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Pattern Formation and Mixing Dynamics in Three-Dimensional Non-Boussinesq Solutal Convection

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Motivated by the process of convective mixing in porous media, here we study the pattern-formation and coarsening dynamics arising from dissolution of CO2 in a single-aqueous phase during three-dimensional (3D) Rayleigh-Benard-Darcy convection. Our focus is on comparing the pattern-formation aspects of solutal convection between conditions of constant concentration and constant flux prescribed at top boundary. In the constant-flux case, a low (constant) injection-rate of CO2 is considered, such that all CO2 dissolves and the system remains indefinitely in single phase. We adopt non-Boussinesq, compressible formulation, whereby the nonlinear phase behavior and density variation of mixture as a function of pressure, temperature, and solute concentration are fully accounted for. We perform high-resolution finite element simulations of 3D convective mixing to examine the interplay between the density-driven hydrodynamic instability and the pattern formation at top boundary as well as various cross sections. We find that gravitational instabilities—triggered at the boundary layer by the local increase in density following CO2 dissolution—further develop into columnar plumes of CO2-rich brine because of self-organization of concentration field in the diffusive boundary layer as a cellular network structure irrespective of top boundary type. While such pattern formation occurs at top boundary for the constant-flux case, it can be captured only below the top boundary for the constant-concentration case. By studying the statistics of the cellular network and concentration field, we identify various regimes of finger coarsening over time for both model types, and show the existence of a quasi-steady state where the average cell size at top boundary, or below top for the constant-concentration case, remains constant due to an equilibrium between cell division and merging in correlation with a constant-mixing rate regime. The morphology of mixing patterns in three dimensions for different types of boundary conditions has implications to numerous density-driven problems in fluid mechanics as well as in environmental and geological settings.

References

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Primary authors: AMOOIE, Amin (The Ohio State University); SOLTANIAN, Mohamad Reza (University of Cincinnati); MOORTGAT, Joachim (The Ohio State University)

Presenter: AMOOIE, Amin (The Ohio State University)

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