Three-dimensional finger structure of natural convection in homogenous and heterogeneous porous medium

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Abstract

In carbon dioxide (CO2) geological storage (CGS), dissolution of CO2 into brine aquifers has been regarded as one of the effective mechanisms for increasing the storage security against the potential risk of leakage due to buoyance. The mass transfer rate of convective dissolution is of significance in dealing with carbon sequestration on a large scale, because it directly governs the long-term fate of CO2 injected into saline aquifers.

Three-dimensional visualization of convective mixing due to density difference has been performed using micro-focused X-ray computer tomography (CT) technology. An analogous fluid system that consists of two miscible fluids of NaCl solution and MEG-NaI (MEG doped with sodium iodide because of the X-ray attenuation) has been presented to mimic the process of CO2 dissolving into brine in a porous medium. Plastic resin particles have been packed in a tube of 70-mm inner diameter to 80 mm in height as a porous medium. Several fluid pairs were used in the experiments to change the Rayleigh number in a range of 2600 ~ 31000, which covers representative value at Sleipner in the North Sea. The transverse dispersion coefficient in convective fingers is estimated from the local concentration in convective fingers evaluated from the local CT values of three-dimensional images.

Both in Rayleigh-Bénard convection and Rayleigh-Taylor convection in a homogenous porous medium induced due to density difference leads to the slight fluctuations appeared on the interface then grow into descending fingers. High concentration fingers extend vertical downward with interacting and merging with neighboring because of the transverse dispersion between descending fingers and ascending flows. In Rayleigh-Bénard convection, the boundary conditions at the top boundary are the constant concentration and no flow through the boundary, namely, the solid wall boundary condition. On the other hand in Rayleigh-Taylor convection, the Rayleigh-Taylor instability is induced on the interface between dense fluid on the top and light layers below and fluids convectively mix each other. The boundary where no fluid flow locates infinitely far from the interface. With respect to the these two extreme conditions, at the boundary of a CO2 plume and formation water, the imposed boundary condition is zero velocity and the continuity in the shear stress normal to the boundary. The effect of boundary conditions on the finger structure has been presented.

The effect of transverse dispersion on finger structure has been presented on the basis of the local concentration in fingers during the convective mixing process. The transverse dispersion between downward and upward flows increases with the Rayleigh number, leading to a decrease in finger number density, due to interacting and merging fingers. The results suggest that the concentration gradient in transverse direction is an order of magnitude larger than that in longitudinal direction and independent of Rayleigh number. In present work, Péclet number is in a range of 10^5~10^2.
ratio of transverse dispersion coefficient and molecular diffusion coefficient is correlated to Péclet number with power law, both convection and diffusion contribute to the dispersion. The enhanced transverse dispersion results in an increase of the decrease rate of finger number density. The finger number density is related to transverse dispersion coefficient following with exponential relationship.

The effect of Rayleigh number on finger extension velocity and mass transfer rate has been evaluated. The finger extension velocity increases with the Rayleigh number and it correlates with the characteristic velocity. Dimensionless mass flux, Sherwood number is correlated to Rayleigh number with the power law. We found that the mechanical dispersion gives a strong impact on the reduction in the onset time of the convection as well as the finger extension velocity and mass transfer rate.

We discuss about the effect of heterogeneity on the fingering structure and mass transport of density-driven natural convection. The plastic resin particle with different average diameter has been packed stratified as a heterogeneous porous medium. The heterogeneity of the porous medium has an influence on the figure structure and mass flux.