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Nonlinear waves during an early evolution of CO_2 plume in an aquifer

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Underground storage of CO_2 in saline aquifers results in complicated multiphase buoyancy-driven flows of CO_2 and formation water. There is extended literature addressing late evolution of the CO_2 plume in the regions remote from injection well. In this study, we consider an early period of CO_2 injection when multiphase flows occur near the well, in the bottom-hole zone.

We consider the self-similar Riemann problem in application to axisymmetric injection of supercritical CO_2 through a vertical well. The injection occurs into a horizontal permeable aquifer of infinite lateral extension. In an asymptotic approximation, we construct the solutions of the problem by means of direct numerical simulations. We take into account thermal processes and phase transitions, and the injected CO_2 can be either warmer or colder than the reservoir temperature. The wave pattern propagating from CO_2 injection well in the aquifer consists of up to six nonlinear Riemann (rarefaction) waves and phase discontinuities (shock waves; displacement and temperature fronts). There can be two type of Riemann waves corresponding to different characteristic velocities. The first type corresponds to isothermal flow, whereas the second type is responsible for temperature alterations and phase transitions. We determine qualitatively different solutions depending on initial reservoir temperature and injection parameters, and we demonstrate solutions in which reservoir and injection parameters are similar to parameters at several existing storage sites. Each type of the solutions corresponds to a specific flow regime in the bottom-hole zone. Due to phase transitions, temperature distribution can be non-monotonic when moving away from the injection well. We investigate the influence of the pressure increase around CO_2 injection well on the flow regimes. Finally, we evaluate accuracy of the asymptotic solution by its comparison with the results of direct numerical simulations.

The solutions of the Riemann problem can be applied only for small gravity numbers at early times when buoyancy can be neglected. For a constant injection rate, a later time corresponds to a higher gravity number for which buoyancy must be taken into account. We investigate numerically the influence of buoyancy on propagation of the shock waves and extended zones corresponding to the Riemann waves of different types. The transition from early to later times and associated CO_2 spreading along the caprock can result in a complicated alteration of the wave-pattern predicted by solution of the Riemann problem.

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