Gas Exsolution and Flow during Supersaturated Water Injection in Porous Media: Experiments and Simulations

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Abstract

Injection into the saturated zone of an aqueous phase that is equilibrated with gas at a pressure higher than the subsurface pressure – a process hereafter referred to as supersaturated water injection (SWI) - is novel and hitherto unexplored way of introducing a gas phase in the subsurface. During SWI, departure from thermodynamic equilibrium between water and gas at the aquifer pressure results in nucleation of gas bubbles within soil pores. These bubbles grow in volume as a result of continuous transfer of solute mass from the injected aqueous phase, resulting in accumulation of the gas phase, which becomes mobile when the magnitude of buoyancy and viscous forces acting on it exceeds the magnitude of capillary forces opposing its movement. Whereas gas phase mobility during in situ air sparging (IAS) has been the subject of extensive studies, very little is known about the dynamics of gas exsolution and flow during SWI in porous media at the continuum scale. Motivated by potentially important applications of SWI in the delivery of reactive gases for in situ bioremediation, as well as the recovery of immobile non-aqueous phase liquids trapped in the form of ganglia below the water table, the present study addresses the experimental observation and continuum modeling of SWI in packed columns.

A series of laboratory experiments were conducted in which an aqueous phase supersaturated with CO_2 was injected at the bottom of long, vertically-oriented, columns packed with sand or glass beads and initially saturated with de-gassed water. The grain size of the packing, as well as the flow rate and carbon dioxide content of the injected aqueous phase were varied, whereas the gas and water effluent rates and column inlet pressure where continuously recorded. Additionally, the dissolved-CO_2 concentration of the aqueous phase at different locations in the column, and the average gas saturation of the column were measured. The experiments provided data pertinent not only to steady-state SWI operation, but also to transients associated with start-up and shut-down of SWI. All experiments were simulated using a compositional multi-phase flow code (CompFlow) using values of the porosity and permeability of the packed columns and aqueous phase relative permeability data determined from independent experiments. Non-equilibrium transfer of CO_2 mass between the aqueous and gas phase was described using an experimentally-determined mass transfer correlation (Nambi and Powers,

2003), with modifications necessary to capture bubble nucleation within the context of continuum modeling. Only the dependence of gas relative permeability on saturation was adjusted in the model to achieve agreement with the experimental data. The same gas relative permeability function was found to describe all experimental observations, lending support to the hypothesis that SWI results in compact patterns of immiscible displacement of water by gas, for which a Darcy's law treatment using saturation-dependent relative permeabilities, such as those of Buckley-Leverett, is appropriate. This finding is in accord with pore scale simulations of the process and is attributed to the stabilizing effects of mass transfer on multiphase flow. The finding is particularly significant because the alternative means of introducing a gas phase in the subsurface by IAS is known to result in channelized gas flow that is difficult to describe using continuum models. To further illustrate the potential of an experimentally-validated continuum model of SWI, simulations of the recovery of residual LNAPL from a packed column by SWI are compared to experimental data.