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Estimating effective rates of convective mixing from commercial-scale injection

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Primary trapping mechanisms in the context of geologic storage of carbon dioxide (CO_2) are often considered to be those of structural, capillary and solubility trapping. Structural trapping refers to immobilization due to (near-horizontal) low-permeable barriers, which are related to the large-scale topography. Further, solubility trapping is considered as dissolution of CO_2 into formation brine. Finally, capillary trapping is immobilization of CO_2 in a residual state due to interfacial tension effects between free-phase CO_2 and brine, which is a local effect on the millimeter and centimeter spatial scales.
Different mechanisms contribute to the process of dissolution. Firstly, there is diffusion of CO_2 in the brine phase, which allows more CO_2 to dissolve in the brine. Secondly, dissolution of CO_2 into brine induces an increase in brine phase density. This creates a gravitationally unstable convection of brine saturated with CO_2 above less dense brine, which can transport CO_2 downward while driving brine with low CO_2 concentration upwards. This convection is referred to as convective mixing and the mechanism accelerates the rate at which CO_2 is dissolved.
We understand that the contribution of each trapping mechanism to the total trapping depends on a combination of several physical processes that are active on widely different spatial and temporal scales. This results in challenges when it comes to modeling and simulation of this system. To overcome these challenges upscaled models for CO_2 migration that in addition to the standard two-phase flow physics includes dissolution, effective convective mixing and capillary trapping are derived in the literature. These models require as input the effective upscaled convective mixing rates. For stationary conditions, this can reasonably be taken from high-resolution simulations. However, no validation of these simulations exists at the field scale, and no data exist at all (either computationally or experimentally) for unsteady conditions.
In this work we consider the ongoing Utsira (Sleipner) injection as a large-scale experiment, and rely on analysis of gravimetric data to provide us with measured data. Utilizing an upscaled model on the available geometric, petrophysical and measured data we get the first field-scale estimates of the effective upscaled convective mixing in the context of CO_2 storage. To account for the uncertainties in the description of the storage formation, sensitivity studies are conducted relative to some of the most uncertain parameters.
Our results give upscaled convective mixing rates on the order of 15 kg/m^2/y. These numbers are comparable, but somewhat higher, than previous analysis using high-resolution numerical simulations would indicate. As such, our work validates the use of numerical simulations to obtain upscaled convective mixing rates, while at the same time yielding validation of convective mixing as an important, and quantifiable storage mechanism in the Utsira formation. Furthermore, we consider projections into the future with the obtained upscaled convective mixing rates.