Convective mixing in formations with horizontal barriers

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ABSTRACT

It has been shown that convective mixing in porous media flow is important for applications such as saltwater intrusion and geological storage of carbon dioxide. In the latter case, dissolution from the injected phase to the resident brine is assisted by convective mixing, which leads to enhanced storage security through reduced buoyancy. Here, we focus on the effect of horizontal barriers on the efficiency of convective mixing. Previous investigations of the effect of heterogeneity on mixing efficiency have focused on random permeability fields or barriers of small extent compared to the intrinsic finger wavelength. The effect of horizontal barriers of larger extent, such as mudstone inclusions or thin shale deposits, has not been given sufficient attention. We perform detailed numerical investigations to represent the continuous solution of this problem in semi-infinite domains with barriers arranged in a periodic manner. The results show that mass flux into the domain, which is a measure of the efficiency of redistribution of the solute, is inversely proportional to the barrier length and proportional to the horizontal and vertical aperture between the barriers, for the cases studied. The flow structure is complex, and it depends not only on the total area of barriers but also largely on the distribution of barriers. Therefore, neither simple analytical models nor simple upscaling methods that lack information about the flow paths, can be used to predict the behavior. However, we compute the effective vertical permeability by flow-based upscaling and show that it can be used to directly obtain a first-order approximation to the mass flux into the domain.

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1. Introduction

One method to reduce atmospheric emissions of carbon dioxide (CO_2), a greenhouse gas, is to capture the gas from large-scale point sources and inject it into geological formations such as saline aquifers. Several physical features of the fluids and the rock sequester CO_2 in the pores of the rock for geologic time-scales. For example, dissolution into brine increases brine density and thereby reduces the risk of upward migration. This is referred to as dissolution trapping, and has shown to be an important trapping mechanism in typical geologic storage scenarios [1–3].

The efficiency of dissolution trapping is largely impacted by density-driven convective mixing. Convectively-enhanced CO_2 dissolution has been studied extensively in homogeneous systems (e.g. [4,5]). Real storage formations are heterogeneous in permeability and porosity and this may affect the efficiency. Ranganathan et al. [6] showed that the redistribution of solute in domains with random heterogeneity can be described in terms of different flow regimes (fingering, channeling, and dispersive flow) depending on the permeability field. Farjazadeh et al. [7] also studied the effect of random heterogeneity fields. With numerical simulations they found that heterogeneity implied enhanced dissolution rates compared to a homogeneous case with the same average permeability. However, thin shale deposits or mudstone inclusions in sandstone aquifers rather act as flow barriers [8–10], causing horizontal dispersal of the flow field and therefore reduced vertical mixing. In these settings, heterogeneity may reduce the efficiency of dissolution trapping, rather than enhance it.

Some recent studies have investigated the impact of flow barriers on density-driven convection. Green and Ennis-King [11] showed that the dissolution rate in aquifers with horizontal impermeable barriers of small lateral extent relative to the finger widths can be modelled approximately based on an anisotropic permeability that uses the reduced effective vertical permeability. Post and Simmons [12] studied the effect of low-permeability lenses of larger extent on sequestration of a solute (salt in their case) in the low-permeability strata. They found that for permeability contrasts of two orders of magnitude or larger between the high- and low-permeability strata, salinisation of the low-permeability strata was governed by diffusion. They also found that at late times, if the domain is flooded by fresh water, solute may reside mostly within the low-permeability strata. However, the focus of their work was

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not on the overall dissolution rate, and thus the mixing efficiency in systems with barriers of relatively large horizontal extent is still unknown.

To address these open issues, we perform numerical simulations to investigate the mixing efficiency in aquifers with horizontal barriers of primarily larger extent than the intrinsic wavelength of unstable fingers, see Fig. 1. We focus on the effect that these barriers have on the dynamic fingering process and mixing efficiency. We call the mass flux of solute into the domain the dissolution rate because in CO_2 storage, it will correspond to the rate of CO_2 dissolved from the plume to the brine. The dissolution rate is therefore a measure of the efficiency of dissolution trapping and can be used as input to large-scale models of CO_2 migration such as used by Gasda et al. [2] for the Johansen formation in the North Sea. Although our focus is on geological CO_2 storage, the results are generic with respect to the solute, and can be used also to model other phenomena such as the distribution of salt.

The simulations in heterogeneous domains are quite slow and we limit this investigation to two-dimensional flow. However, upscaling possibilities, needed for later 3D simulations, are discussed. We also discuss possibilities for use of analytical methods. For example, Hesse and Woods [9] presented analytical results to gravity driven two-phase flow in heterogeneous domains similar to the ones investigated for our miscible displacement problem.

In Section 2 we define the model problem and describe the numerical treatment. The results in terms of dynamic fingering behavior, finger tip speed and dissolution rate for different geometrical configurations of the tight barriers are presented in Section 3. Then, we discuss upscaling possibilities in Section 4, and apply the results to dissolution trapping in the Utsira formation. The main conclusions are summarized in Section 5.

2. Model problem and numerical treatment

We focus on the effect of the barriers on the redistribution of a solute (e.g. CO_2) within the water phase. We consider a solute source (e.g. a CO_2 plume) along the top boundary of the domain. The problem is modelled by Darcy's law, a transport equation for the solute, the Boussinesq approximation and a linear density dependence on concentration:
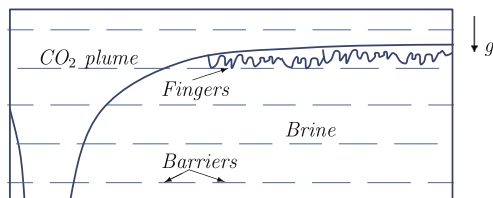
$$\mathbf{u} = -\frac{K}{\mu}(\nabla P - \rho \mathbf{g}), \tag{1}$$

$$\phi \partial_t c = -\mathbf{u} \cdot \nabla c + \phi D \nabla^2 c, \tag{2}$$

$$\nabla \cdot \mathbf{u} = 0, \tag{3}$$

$$\rho = \rho_0 + \Delta \rho c. \tag{4}$$

Here, $\mathbf{u}$ denotes the Darcy velocity, K the permeability, μ the viscosity, P the pressure, $\mathbf{g}$ the vector of gravity, ϕ the porosity, D the diffusion coefficient, ρ_0 the minimum density and $\Delta \rho$ the maximum density difference induced by the solute. The concentration c is

scaled to values between zero and one, where the latter represents the solubility limit, m. The chosen linear relation between CO_2 concentration and density of the water is motivated by experiments [13].

The tight barriers are modelled by internal no-flow boundary conditions and hence we do not solve the equations within those regions. All properties therefore refer to the homogeneous isotropic aquifer surrounding the barriers. The equations are further scaled by the characteristic velocity $u_c = K\Delta\rho g/\mu$, length $l_c = D\phi/u_c$ and time $t_c = D\phi^2/u_c^2$. In addition, the nondimensional pressure p is related to P by $P = (D\mu\phi/K)(p + (\rho_0/\Delta\rho)z)$, where z is the nondimensional depth. With our choice of scaling, we obtain a parameter-free nondimensional form of the equations:
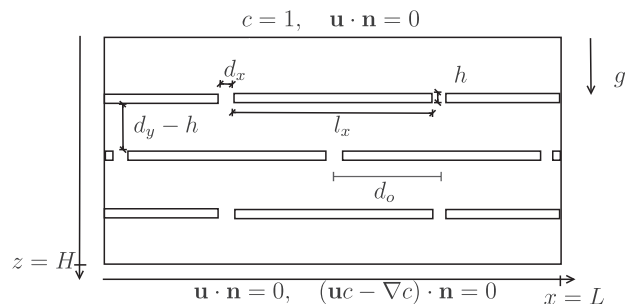
$$\mathbf{u} = -(\nabla p - c\mathbf{e}_z), \tag{5}$$

$$\partial_t c = -\mathbf{u} \cdot \nabla c + \nabla^2 c, \tag{6}$$

$$\nabla \cdot \mathbf{u} = 0. \tag{7}$$

The choice of representing the shale barriers as no-flow regions is an approximation of the real system. Given the large contrast between permeability in e.g. sandstone and shale [14], advective flow through the barriers is likely to be small. Diffusive interaction between the high- and low-permeability strata may contribute to transport at late times [12] but is neglected here. In addition, our choice facilitates comparison with analytical models, and is helpful for understanding the dissolution based solely on the geometric configuration of the barriers, which is our focus.

Fig. 2 displays the boundary conditions and schematic of the barrier heterogeneity for our two-dimensional setting. The constant concentration top boundary condition approximates the dissolution of CO_2 from the supercritical plume above the domain. Advective exchange with the source (e.g. a two-phase region) is neglected here for simplicity, corresponding to zero relative permeability for the water in the source zone. However, it should be noted that the effect of mobile water in the two-phase zone can increase the dissolution rate in CO_2 storage, as described in [15]. For the side- and bottom boundaries, we prescribe no-flow conditions. The size of the domain and the simulation time are chosen large respectively small enough to make the impact of these boundaries small, cf. below. The flow field around the fingers is local [4] and therefore we expect the flow to be essentially undisturbed by the bottom boundary until fingers are close to the bottom, which is the end time of the simulations. As for the impact on the dissolution rate, independence on domain size was shown in a previous paper [16] to exist also for some time after fingers reached the bottom of the domain.

Fig. 1. With tight horizontal barriers in the aquifer, fingers of water with high CO_2 concentration under the buoyant plume will pool above the barriers. Downward finger migration is restricted to the openings between the barriers.

Fig. 2. Nondimensional model domain, including sample thin barriers, and boundary conditions. The bottom boundary condition (no-flow) is also applied to the side boundaries and to the barriers. d_o is the horizontal distance between center of barriers.