Vertical Fingering in Porous Media
Effects of Inhomogeneity and Anisotropy

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Introduction: Storage of CO2 in the sub-surface is seen as a technology that can contribute to the generally accepted goal of a de-carbonized society. As real field experiments are hardly feasible, many current studies utilize the capabilities of numerical modelling. Concerning the practical application of CO2 storage many questions are still unanswered. In the most favoured scenario CO2 concentrated in a brine is pressed into a deep geological formation. Eventually the brine will start to dissolve into the deeper layer by diffusion. Increasing concentrations in the lower layer will induce convective patterns, which in turn influence the diffusive transport into the aquifer..

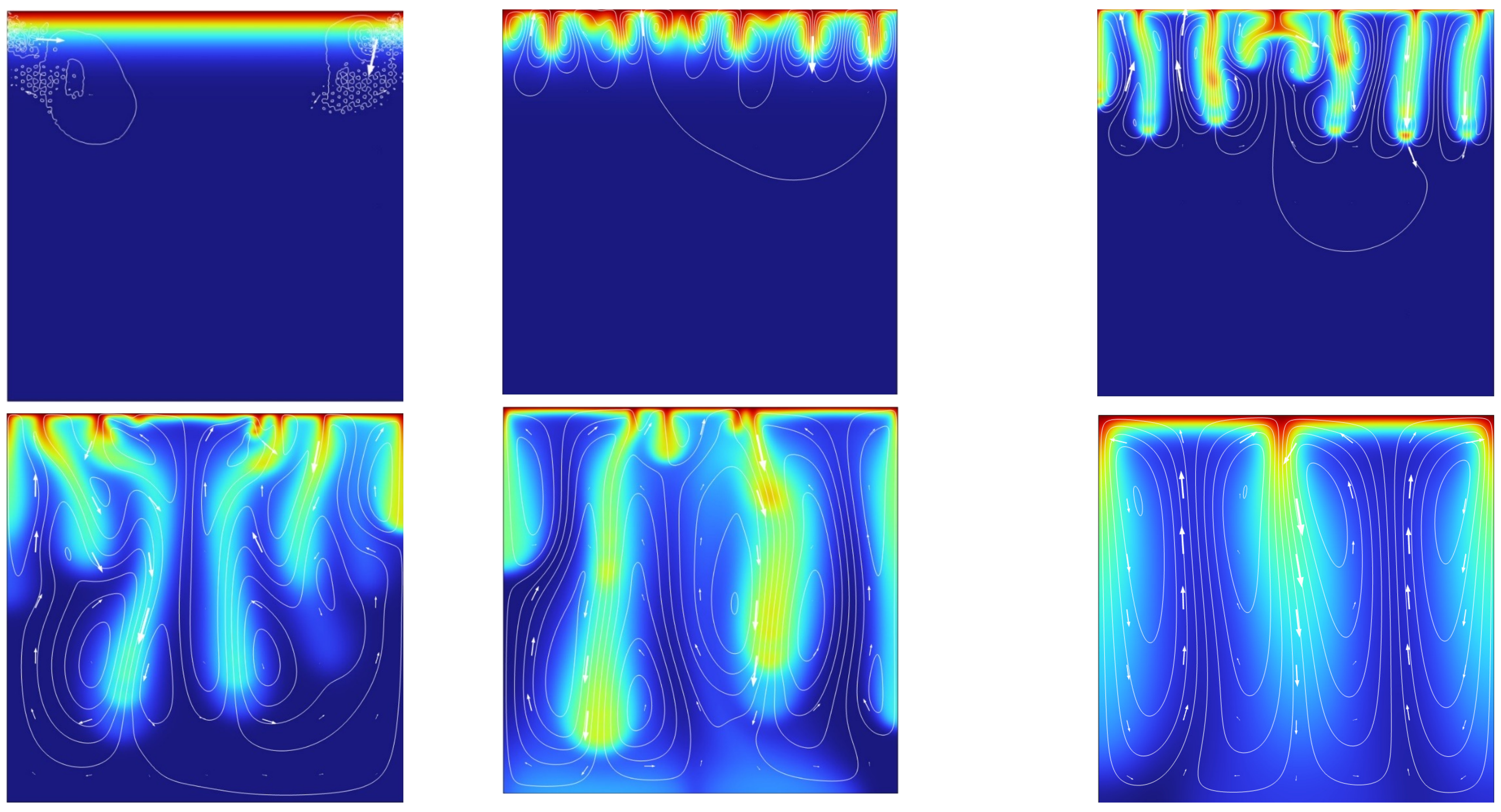


Figure 1. Finger development in time, from top left to bottom right, visualized by concentration (red: high, blue: zero) and streamlines; Computed for isotropic and homogeneous conditions and Ra=2050

Convection is a multi-physics phenomenon, in which flow and transport processes are coupled. For the coupling the fluid density is the crucial parameter. For the highly dynamic processes of CO_2 storage, with high Rayleigh number, the initial phase with pure diffusion is followed by a convection phase. The latter can be sub-divided in an early stage with high but fluctuating mass transfer; and a late stage, in which salt transfer is decreasing[2].

Differential equations: Flow and transport are described by a non-linear set of coupled partial differential equations: (1) for the streamfunction Ψ, and (2) for the normalized concentration c[1,3]:

$$\frac{\partial}{\partial x}\left(\frac{\mu}{k_z}\frac{\partial \Psi}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{\mu}{k_x}\frac{\partial \Psi}{\partial z}\right)=-g\frac{\partial \rho}{\partial x} \qquad (1)$$

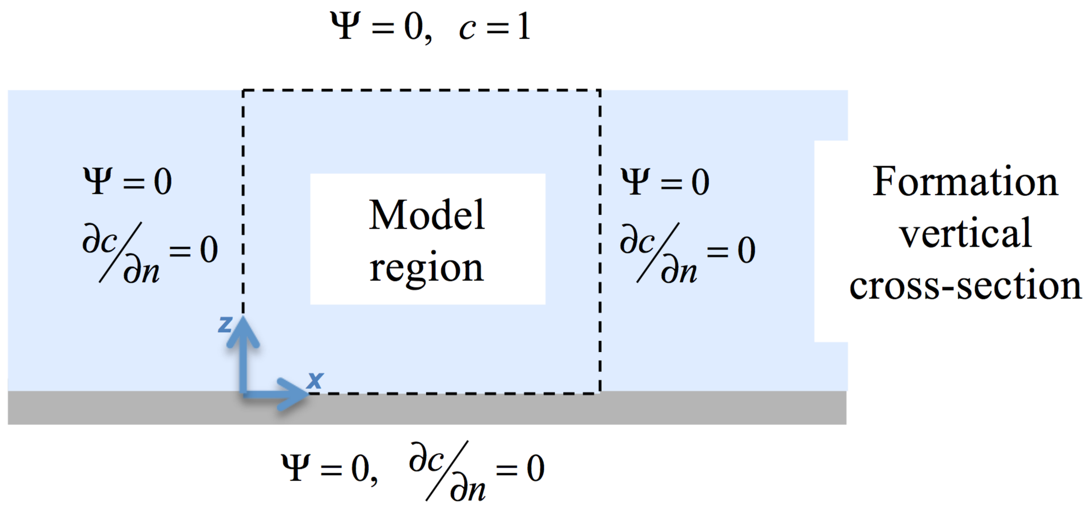
$$\frac{\partial c}{\partial t}=\nabla\cdot\left(D_x\frac{\partial c}{\partial x}+D_z\frac{\partial c}{\partial z}-\mathbf{v}c\right) \quad \text{with} \quad \mathbf{v}=\left(-\frac{\partial \Psi}{\partial z},\frac{\partial \Psi}{\partial x}\right)^T \qquad (2)$$

Non-dimensionalization of the equations leads to the introduction of the dimensionless Rayleigh number Ra as determining parameter[4].

$$Ra=\frac{gk_x\Delta\rho H}{\mu D_z}$$

Figure 2 shows the 2D model region within a vertical cross-section through the permeable formation and the boundary conditions.

Figure 2. Model region & boundary conditions



Parameter	Value [Unit]	Parameter	Value [Unit]
Saturated CO_2 mass fraction	0.0493	Density difference $\Delta\rho$	10.45 kg/m^3
Viscosity μ	0.5947•10^{-3} Pa•s	Molecular diffusivity D	2•10^{-9} m^2/s
Brine density	994.56 kg/m^3	Permeability k *(mean value)*	5•10^{-13} m^2

Table 1. List of reference case parameters[4]

Results: The effect of inhomogeneity, realized by random distributions, was explored, as well as anisotropies in permeability and diffusivity. For input parameters see Table 1.

Figure 3 depicts the temporal development of mass transfer into the aquifer, represented by the dimensionless Sherwood number Sh, for isotropy and 4 ratios of anisotropy. After an initial phase of pure diffusive entry the onset of convection can be identified by the steep rise of Sh. Dots represent outputs from 11 inhmogeneity scenarios for each anisotropy case. Simulations were performed with Ra = 2050.

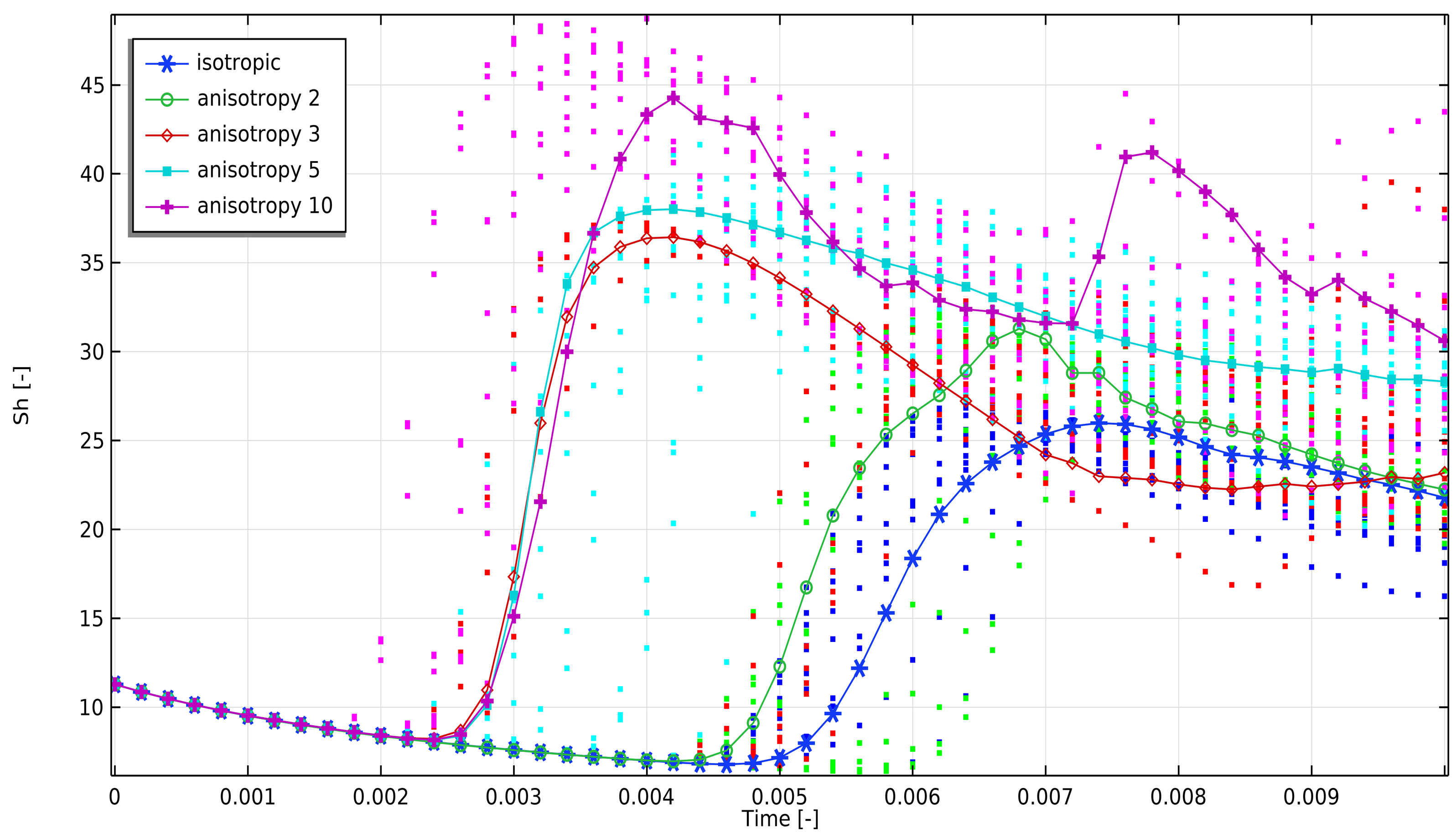


Figure 3. Mass transfer as function of time for homogeneous (curve) and inhomogeneous cases (dots)

Conclusions: The details of the flow patterns depend strongly on disturbances of physical parameters. Despite the differences in the single scenarios the duration of the early convection stage turns out to be a constant. In the late convection stage the range of fluctuations is decreasing.

References:

1.Farajzadeh, R., Salimi, H., Zitha, P., Bruining, H., Numerical simulation of density-driven natural convection in porous media with application for CO_2 injection projects. *Intern. Journal of Heat and Mass Transfer* 2007. 50: 5054–5064
2.Soboleva, E., Instability problems and density-driven convection in saturated porous media linking to hydrogeology: a review. *Fluids* 2023, 8, 36
3.Holzbecher, E., *Modelling Density-Driven Flow in Porous Media*,, Springer Publ., Heidelberg, 1998
4.Holzbecher, E., Modeling pathways and stages of CO_2 storage, *Int. Journal of Multiphysics* 2016, 10(4): 397-415