THE LONG-TERM FATE OF CO$_2$ INJECTED INTO AN AQUIFER

Erik Lindeberg and Per Bergmo
SINTEF Petroleum Research, NO-7465 Trondheim, Norway

ABSTRACT

Assuming that an underground aquifer is capped by a capillary seal preventing injected CO$_2$ to migrate into the atmosphere, the CO$_2$ will eventually accumulate under this seal. The topography of the seal will determine the CO$_2$ migration on the 1000 years time-scale. CO$_2$ diffusing into the underlying aquifer column will set up convective currents in the aquifer enhancing the solution rate of CO$_2$. Most of the CO$_2$ will have dissolved into the aquifer after between 5000 and 50000 years mostly dependent on the vertical permeability of the aquifer and the contact area between CO$_2$ and brine. On a time scale of several hundred thousand years, molecular diffusion through the capillary seal will be the dominating transport mechanism and will eventually deplete the formation of CO$_2$ by transporting it into the atmosphere if reactions between CO$_2$ and rock minerals are neglected. This process will take millions of years, however.

INTRODUCTION

5 million tonnes CO$_2$ from the Sleipner gas processing plant has been injected into the Utsira formation [1] in the North Sea and eventually 25 million tonnes will be injected before the gas production has ceased. The CO$_2$ is injected near the bottom of the approximately 200 m thick sand. The migration of injected CO$_2$ is being monitored by 4D seismic, which shows that the CO$_2$ is retained in large thin clouds under what is expected to be horizontal semi-permeable shales within the formation. All evidences [2] are indicating that the intermediate shales are not sufficiently tight to prevent most of the CO$_2$ from migrating to the top seal of the formation after the injection period is over. The topography of the top seal will determine the further migration. The questions how fast CO$_2$ will dissolve in the brine and what the long-term fate of the CO$_2$ will be, have been raised and are the subject of this study.

MODELLING

Selection of area for the model

Based on 12 000 x 10 000 m pre-injection seismic maps of the top seal and floor of the formation, and one intermediate shale layer within the formation a reservoir model was constructed. The seismic maps had an initial resolution of 12.5 x 12.5 m. In a previous study [2] a subset of this grid (2000 x 3000 m, coarsened to 25 x 25 m) was used to simulate the near injection site and this model was large enough for predicting the first 10 years of injection. Due to the smooth topography of the top seal (depth variation of less than 80 meter over the 120 km$^2$ area) the CO$_2$ will spread over a very large area. To predict the long-term fate of the injected CO$_2$ this requires the use of a much larger model and using a coarser grid to achieve acceptable computing time. In addition, the resolution has to be sufficiently fine to preserve the dominating migration pattern under the seal. Determining the optimal lateral coarsening and selecting the optimal part of the reservoir was performed in several steps. As a reference, a simulation grid with 25 x 25 m lateral resolution was used. By simulating the migration of CO$_2$ on a subset of the complete grid consisting of only the upper 30 m of the formation with a 2 m vertical resolution the area could be reduced to a 7.2 x 9.8 km while still containing the CO$_2$ bubble within the model. Next, the lateral grid was coarsened. With 100 x 100 m grid blocks, the migration pattern was satisfactory maintained. The lateral grid was now limited to approximately...
7,000 grid blocks which allowed the use of 52 vertical blocks (Figure 1). With a total of 350,000 grid blocks a satisfactory compromise between resolution and computing speed was achieved when simulating the problem with the parallel option in Eclipse 100 using 10 processors on a SGI Origin 2000.

Figure 1: Reservoir grid. The dark spot represent the extension of the CO₂ bubble under the cap seal in year 2011 after 15 years of injection

Simulation of the combined effect of lateral migration and dissolution of CO₂ into the aquifer
The results of the simulation of the fate of the CO₂ bubble resulting from 25 years of CO₂ injection shows that the CO₂ bubble increases in its lateral extension under the cap seal for more than 200 years after the injection has stopped (corresponding to the six first top view pictures in Figure 2). After 200 years the dissolution is the dominating mechanism resulting in a shrinking of the bubble and after another 4800 years the bubbles has completely dissolved. In the base case (Utsira conditions) the horizontal permeability, $k_h = 2000$ mD. The sand is isotropic, but the semi-permeable shales has been up-scaled through the vertical permeability, $k_v = 200$ mD. Simulations where both $k_h$ and $k_v$ were reduced with a factor of respectively 0.1, 0.01 and 0.001 was also performed resulting in a much lower dissolution rate. The relative dissolution rates are illustrated in Figure 3.

Induced convective currents in the aquifer column
Molecular diffusion can usually be neglected in reservoir engineering especially when large reservoir models are considered because diffusion is generally negligible compared to other fluxes. In this case with dissolution in an underlying brine column molecular diffusion play a significant role on long time-scales. Due to the special pVT properties of the CO₂/brine system (the density of CO₂ saturated brine is approximately 10 kg/m³ denser than brine with no CO₂) molecular diffusion from the CO₂ bubble into the underlying brine column will create a hydrodynamic unstable layer setting up convective currents in the brine column [3]. These convective currents will carry dissolved CO₂ down into the column and undersaturated water up to the CO₂/brine contact enhancing the transfer of CO₂ into the brine compared to a transport relaying on molecular diffusion only. Due to the importance of this mechanism, a more thorough examination of the phenomena has been performed by some numerical experiments.

The convection was simulated on a 10 m wide and 13 m deep 2D model. This corresponds to the region of the CO₂/brine contact were a 1 m thick CO₂ bubble is resting on top of a brine column at the pressure and temperature corresponding to reservoir conditions in Utsira. Figure 4 shows how CO₂ dissolves in the brine.
Figure 2: The migration of CO$_2$ under the cap seal in year 2021 (end of injection), 2050, 2150, 2200, 2520 (maximum), 3620, 5020, and 5820

\[ f = 0.99325 e^{-t/1078} \]

Figure 3: The reduction of free CO$_2$ as function of time at varying permeabilities. $k_v/k_h = 0.1$ for all tests.

column in one-year intervals. The initially sharp boundary between the gas bubble (black) and the brine (white) is gradually becoming diffuse and after two years, the first instabilities are seen in the diffusion zone. Plumes with a characteristic minimum width are formed. These consist of brine with high concentration of CO$_2$. They penetrate into the brine with less CO$_2$ and gradually coalesce into larger plumes. New small plumes are formed which also merge into larger entities during migration. The effective dissolution rate is dependent on the horizontal grid. By reducing the grid block size stepwise, the minimum grid block size was determined from how the solution converged. The horizontal grid block size had to be approximately 0.2 of the wavelength of the initial formed plumes to give an acceptable convergence. The following simulations were performed with a grid of 200 x 340 grid blocks and with a grid block size of 4 x 5 cm.
Figure 4: Profile of the convection of high-density plumes of CO$_2$-rich brine into the brine column below

Numerical experiments on models with different permeabilities, $k$, and viscosities, $\mu$, were performed. In Figure 5 an example is plotted with a table of simple empirical relations for convection and onset of convection that were found. The plume convection is much stronger than diffusion only, but somewhat weaker than a pure Darcy flow, probably due to transverse mixing.

Figure 5: Dissolution of CO$_2$ due to convective flow. In this example $\mu = 0.885$ mPa s, diffusion coefficient, $D = 2.06 \cdot 10^{-9}$ m$^2$/s, the porosity $\Phi = 0.38$ and the solubility of CO$_2$ in brine, $c_0 = 52.94$ kg/Sm$^3$.
Induced convective currents in a 3D reservoir case

In the reservoir simulations above the shrinkage of the CO$_2$ bubble is due to convective dissolution of CO$_2$ at the CO$_2$/brine interface. Considering the high resolution of the grid needed to give a fair representation of the problem and that the lateral grid block size is 100 m x 100 m in the reservoir simulation, the question of how accurate the CO$_2$ dissolution is represented must be addressed. In Figure 5 the plume of dissolved CO$_2$ is illustrated at different time-steps. In the first 100 years no significant convection occurs. This artefact is due to that the convection will not start before the instability is so large that it can be represented by the large plume wavelength (200 m). When this instability is reached the convection progresses in the same way as illustrated before with coalescing plumes. The convection delay of approximately 100 years does not play a significant role considering all the other uncertainties of the reservoir model, however. The explanation for the slower dissolution rate in the reservoirs (Figure 3) within lower permeability is not only due to the slower induced convection, but also because the CO$_2$ distributes over a smaller area resulting in a smaller contact area between CO$_2$ and brine.

![Image](image1.png)

**Figure 5:** A 3D view of the convection of CO$_2$ rich brine plumes into the column below at year 2220, 2420, 2620, and 5020 when all the plumes have coalesced into one single plume unit. The big plume in the middle on the upper two pictures is near to the injection site.

DIFFUSION OF CO$_2$ THROUGH THE OVERBURDEN INTO THE BIOSPHERE

A capillary seal in a shale or mudstone is an effective barrier for CO$_2$ in gas phase due its high capillary entrance pressure. These seals provide, however no restriction for molecular diffusion because their pores are saturated with brine and they can have a large porosity. Above Utsira there is a 700 m thick overburden between the seafloor and the aquifer. The concentration profile of CO$_2$ in the overburden is obtained by solving the one-dimensional diffusion equation for a porous medium with tortuosity, $\tau$,

$$\frac{\partial c}{\partial t} = D_z \frac{\partial^2 c}{\partial z^2}, \quad c(0,t) = c_0, \quad c(Z,t) = 0 \text{ for all times } t, \text{ and initially } c(z,0) = 0$$

(1)
where \( c \) is the concentration of CO\(_2\), \( z \) is the height-coordinate, and \( D_c = D / \tau \) is the effective diffusion coefficient. The bulk diffusion coefficient of CO\(_2\) in brine \( D \) is set equal to \( 2 \cdot 10^{-9} \text{ m}^2/\text{s} \). At these boundary conditions, Eqn. 1 has the solution

\[
c(z, t) = c_0 \left[ 1 - \frac{z}{Z} - \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin \left( \frac{n \pi z}{Z} \right) e^{-D_c \left( \frac{n \pi^2}{Z^2} \right) t} \right]
\]  

(2)

The flux, \( J \), in a porous medium with porosity, \( \Phi \), from the top seal of the formation into the atmosphere is obtained by combining the flux equation and the derivative of Eqn. 2 for \( z = Z \):

\[
J = -D_c \Phi \left( \frac{\partial c}{\partial z} \right)_{z=Z} = D_c \Phi c_0 \left[ \frac{1}{Z} + \frac{2}{Z} \sum_{n=1}^{\infty} (-1)^n e^{-D_c \left( \frac{n \pi^2}{Z^2} \right) t} \right]
\]  

(3)

The escape rate as function of time is plotted in Figure 6 assuming that the CO\(_2\) bubble has a constant radius of 2 000 m. It will take more than 500 000 years for the CO\(_2\) to reach the surface and the maximum flux rate is not achieved until the steady state concentration profile is reached after several million years. This illustrates the effective trapping of CO\(_2\) in an aquifer as soon as it has dissolved in the brine and suggests that injection of CO\(_2\)-saturated brine could be a feasible option for CO\(_2\) storage if the seal integrity is questionable.

![Diagram of CO2 escape rate](image)

6: Molecular diffusion through the overburden seal. The escape rate is calculated from Eqn. 3 assuming that the CO\(_2\) source is a bubble with constant radius of 2 000 m

CONCLUSION

The long-term fate of CO\(_2\) in an aquifer will strongly depend on the topography of the cap rock. The CO\(_2\) will eventually dissolve in the brine and this dissolution is mainly controlled by induced convective currents. If mineral reactions and hydrodynamic activity are neglected, the dissolved CO\(_2\) represents the ultimate trapping of CO\(_2\) because molecular diffusion of CO\(_2\) through the overburden rocks is too slow to have any climate impact at a time-scale shorter than the long ice-age cycle (100 000 years).

REFERENCES