

Electromagnetic Monitoring of CO₂ Storage in Deep Saline Aquifers - Numerical Simulations and Laboratory Experiments

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1 Introduction

The knowledge of petrophysical parameters and their contrasts is crucial to reliably monitoring CO₂ storage processes. The electrical conductivity appears to be a sensitive indicator for a resistive gaseous or supercritical CO₂ phase replacing a conductive pore fluid in a porous medium like a saline sandstone aquifer. However, detailed knowledge on the influence of supercritical CO₂ on the electrical resistivity of a formation is not sufficiently available yet.

Therefore, we have carried out laboratory experiments to predict the contrast in electrical resistivity due to the presence of CO₂ in an initially water-saturated sand sample resembling the petrophysical situation typical for a reservoir. Furthermore, the expected parameter contrasts were estimated according to empirical equations and numerical simulations (Fig. 1).

On a middle- to long-term perspective, we aim at developing an electromagnetic monitoring technique using a borehole transient electromagnetic sensor which offers a unique opportunity to generate enhanced sensitivity at depth with respect to detecting migrating CO₂ in a reservoir. This work is therefore integrated into national CCS research programs with an interdisciplinary variety of partners.

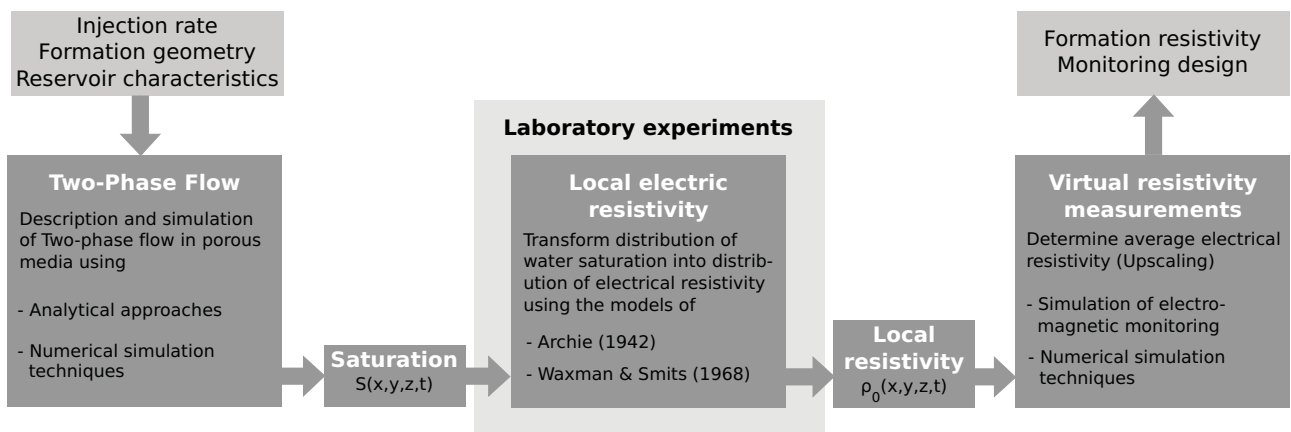


Figure 1: Workflow of the numerical simulation steps necessary for the transformation of water saturation into electrical resistivity.

2 Theory

Two-phase flow is governed by two equations simultaneously enforcing continuity of the water (w) and the CO₂ (co2) phase flow (Busch et al. 1993). Both equations are linked by retention curves $S_e(p_c)$ and relative permeabilities $k_r(S)$, such that

$$\begin{aligned} \nabla \cdot d^w \left[-\frac{\kappa k_r^w}{\eta^w} (\nabla p^w + d^w g \nabla D) \right] &= -\Phi \frac{\partial (d^w S_e^w)}{\partial t} + d^w w_0 \\ \nabla \cdot d^{co2} \left[-\frac{\kappa k_r^{co2}}{\eta^{co2}} (\nabla p^{co2} + d^{co2} g \nabla D) \right] &= -\Phi \frac{\partial (d^{co2} S_e^{co2})}{\partial t} + d^{co2} w_0 \end{aligned} \quad (1)$$

with d as density, κ as intrinsic permeability, η as viscosity, Φ as porosity and g as gravitational acceleration. The link between both phases has been established by experimental data or parameterization,

e.g., by van Genuchten (1980) or Mualem (1976) (with effective saturation S_e , capillary pressure height H_c and parameters α , n , m , L):

$$S_e^w = \frac{1}{(1 + |\alpha H_c|^n)^m} \quad S_e^{co2} = 1 - S_e^w \quad (2)$$

$$k_r^w = (S_e^w)^L \cdot \left[1 - \left(1 - (S_e^w)^{1/m}\right)^m\right]^2 \quad k_r^{co2} = (1 - S_e^w)^L \cdot \left(1 - (S_e^w)^{1/m}\right)^{2m} \quad (3)$$

The resulting distribution of water saturation $S(x, y, z, t)$ can be transformed into electrical formation resistivity ρ using empirical resistivity models, e.g., Archie's law (Archie 1942):

$$\rho = a_1 \cdot \Phi^{-a_2} \cdot S^{-a_3} \cdot \frac{1}{\sigma_w} \quad (4)$$

with σ_w denoting pore water conductivity. Archie's empirical parameters a_1 , a_2 and a_3 strongly depend on rock formation characteristics and can be combined with porosity and water saturation yielding the formation factor F , such that

$$\rho = F \cdot \rho_w. \quad (5)$$

For sands and sandstones with considerable clay content Waxman and Smits (1968) expanded Archie's law to account for both electrolytic conductance and interfacial conductance:

$$\rho = \frac{F^*}{S^n} \cdot \left(\sigma_w + \frac{B \cdot Q_v}{S}\right)^{-1} \quad (6)$$

with a unique formation factor F^* , the counterion mobility B describing the weak dependance of the interface conductivity on pore water salinity and the shalyness parameter Q_v being the cation exchange capacity normalized to the pore volume.

3 Numerical simulation studies

The process of CO₂ sequestration as well as the indication of a successful storage by observation of changes in electrical resistivity has been simulated following the steps indicated by the workflow shown in Fig. 1.

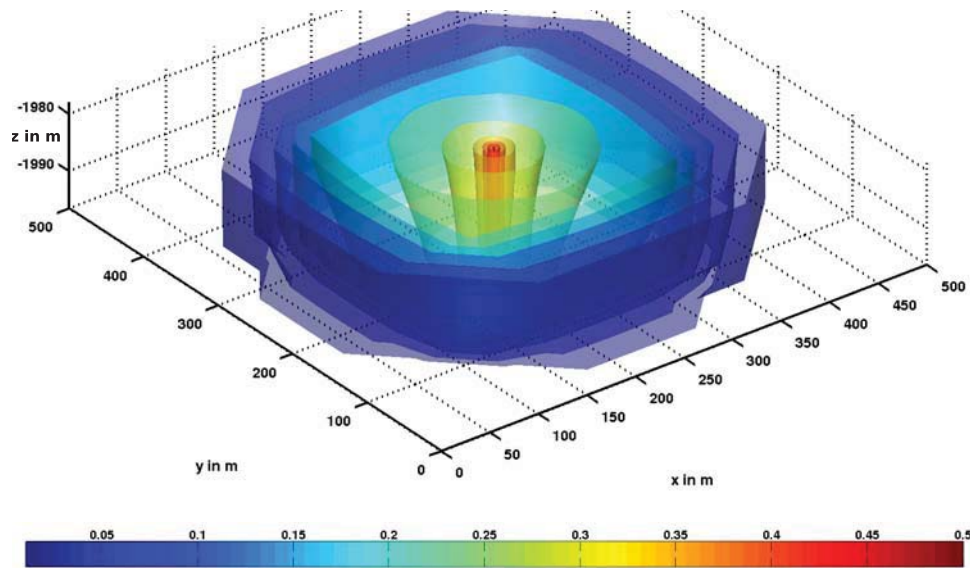


Figure 2: CO₂ saturation after 6 months of constant injection of 1000 m³ per day into a 25 m thick reservoir. The injection well is located at the geometric center. These results were obtained using the FD simulation code Mod2PhaseThermo.

We have incorporated data that is generally available for a CCS site such as the formation geometry, reservoir parameters, e.g. porosity, intrinsic permeability, and injection rates to simulate the injection process. The main result of the numerical simulation studies is an estimate of the temporal changes in the spatial distribution of brine saturation $S(x, y, z, t)$ within a finite computational domain.

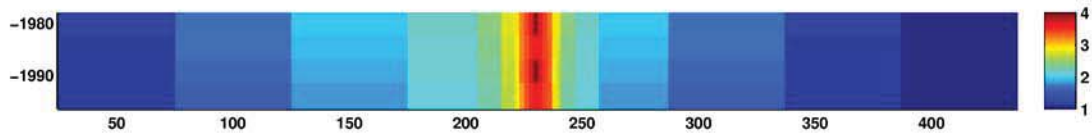


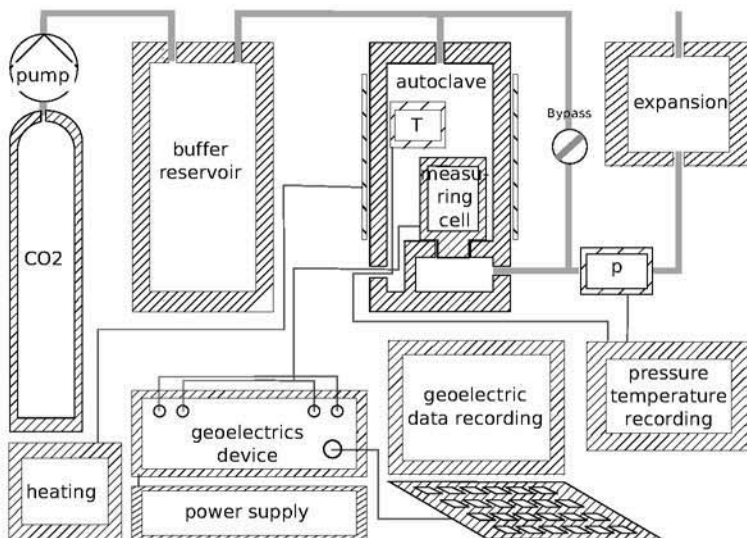
Figure 3: Vertical cross-section through the aquifer indicating the increase in formation resistivity derived from the saturation illustrated in Fig. 2. The transformation was done using eq. (4) and a background resistivity of $25 \Omega\text{m}$ has been considered.

These saturation estimates have later been transformed into local electrical resistivities by means of simple empirical resistivity models. The resulting distribution of local rock resistivity can be used as an input for a numerical simulation of electromagnetic monitoring measurements.

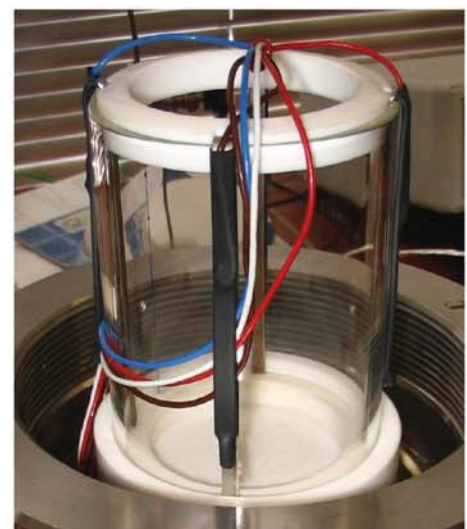
Numerical simulation studies of the injection process have been carried out using the Finite Difference (FD) code Mod2PhaseThermo (Häfner and Boy 2009) as well as the Finite Elements (FE) package COMSOL Multiphysics. Using COMSOL, we were able to model the CO_2 sequestration by a two-phase flow according to eqs. (1)-(3). Under the assumption of negligible compressibility, pressure or temperature induced density and viscosity variations, and chemical interactions between rock matrix, pore water and CO_2 , we have observed a maximum CO_2 saturation of 80 % in the vicinity of the injection well.

The FD code Mod2PhaseThermo simulates multiphase-flow taking into account its thermodynamics and the dissolution of CO_2 in the pore water. The result of such a simulation is shown in Fig. 2. CO_2 saturations of up to 50 % near the injection well can be observed.

Formation resistivities were derived from the observed saturation estimates according to eq. (4) and (6). An increase in resistivity by a factor of 2 to 10 obtained by the COMSOL model and 2 to 4.5 obtained by Mod2PhaseThermo could be predicted, respectively (Fig. 3). In addition to the observed lateral saturation changes, different results have been obtained depending on flow, resistivity model and reservoir characteristics.



(a) Block diagram of the laboratory experiment.



(b) Measuring cell prior to being filled with water saturated sand.

Figure 4: Experimental set-up for the simulation of CO_2 sequestration on a laboratory scale.

4 Laboratory experiments

To validate the results obtained by the numerical studies we have carried out petrophysical experiments on a laboratory scale. For this purpose, an experimental setup has been developed and implemented to carry out a laboratory simulation of the sequestration process (Fig. 4, left). Our intention was to investigate the behavior of supercritical CO_2 under in-situ conditions. Furthermore, we were interested in the validity of the empirical parameters used in eq. (4).

The central element of the apparatus schematically outlined in (Fig. 4) is a measuring cell (Fig. 4, right) inserted into an autoclave allowing for monitoring the apparent electrical resistivity of a sand sample at in-situ pressures and temperatures. In the laboratory assembly, CO_2 was forced to flow through the initially water-saturated sand sample, gradually replacing the pore water. During this process, the electrical resistance of the cell has been recorded with a sampling interval of 10 s. Pressures up to 130 bar were applied at temperatures up to 40°C .

From a practical point of view it might be argued that sand has different petrophysical properties than compact sandstone. However, since sands and sandstones are similar in terms of, e.g., mineral content, grain distribution, and pore space geometry, their electrical properties underlie the same physical mechanisms and can therefore be described by the same petrophysical models (Archie 1942, Schön 1996). Hence, despite substituting sandstone with sand we still expect sufficiently accurate and representative results.

5 Results

A first experiment could prove that pure CO_2 does not show any relevant electrical conductivity at pressures up to 130 bar. During further experiments, CO_2 was lead through an initially water-saturated sand sample resulting in an increase of the electrical resistivity of the sample by a factor of 27 to 33 at pressures up to 50 bar. The remaining electrical conductivity was dominated by a residual water content of 14 to 18 % (Fig. 5).

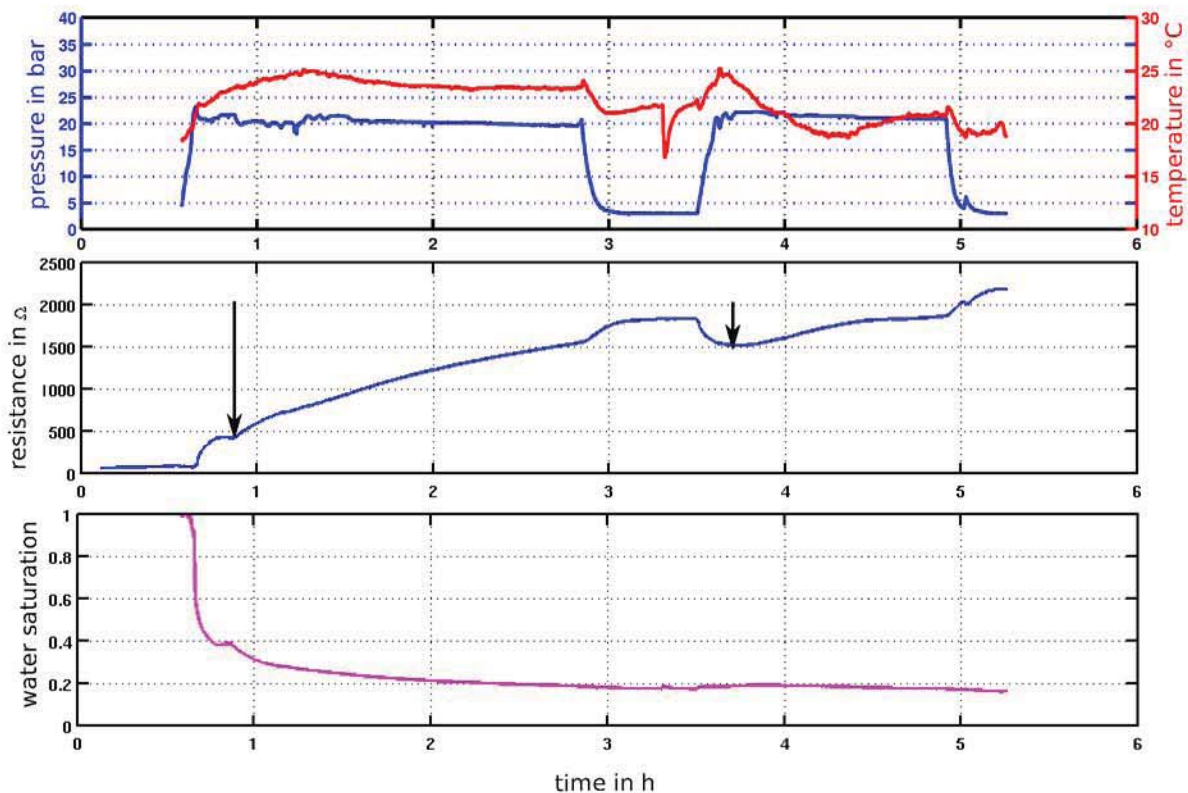


Figure 5: Electrical resistance and water saturation derived according to equation (4) of a sand probe obtained by a flow experiment carried out at a projected maximum pressure of 20 bar and temperature of 25°C . The arrows indicate start of CO_2 injection.

Final experiments have demonstrated that an increase in resistivity may also be achieved under supercritical conditions. However, the sample was not homogeneously infiltrated by the CO₂ and preferential flow paths were built up during the experiment. The pore water has been pressed out only partially, leaving behind tube-shaped flow channels and a very heterogeneous water distribution with average residual water contents of more than 70 %.

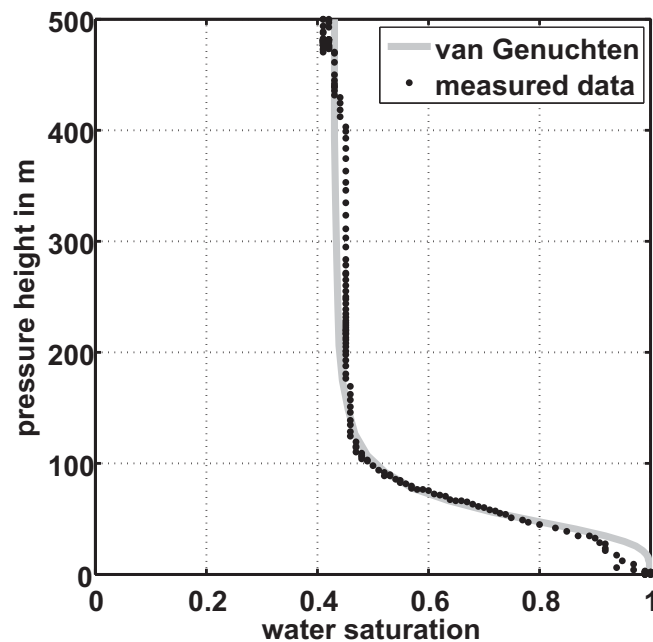


Figure 6: Relation between CO₂ pressure and water saturation derived from data obtained by the initial pressure build-up for an experiment with a projected maximum pressure of 50 bar. The reference data have been calculated according to van Genuchten (1980) with $\alpha = 0.02$ and $n = 3.9$ (cf. eqs. (2)-(3)).

The complications are due to the density of supercritical CO₂ which is large compared to the density of CO₂ in its gaseous state. Consequently, the current experimental assembly causes the high density to result in low flow velocities within the measuring cell. In addition to the flow channels, this effect prevents an effective replacement of the pore water by supercritical CO₂.

The experiments have shown that theoretical pressure-saturation relations can generally be verified in practice using our set-up (Fig. 6). All experimental data sufficiently agree with Archie's law. However, we have to carry out further investigations on the effects of CO₂ dissolving in the pore water. There are indications that this has an important impact on the pore water resistivity depending on pressure, temperature, and brine salinity.

6 Conclusions

Numerical simulation studies and laboratory experiments show that the electrical resistivity of a fluid-saturated porous medium is highly sensitive to the presence of CO₂. Geo-electromagnetic methods are therefore considered as a promising approach for monitoring CO₂ storage.

Still, the laboratory set-up has to be improved further to provide reliable results at high pressures. Subject to these prerequisites, well-founded simulations of electromagnetic monitoring scenarios can be carried out.

Further laboratory experiments will also aim at quantifying the influence of dissolved CO₂ on pore water and formation resistivity. A feasibility study could show whether electromagnetic methods are able to monitor, e.g., an expanding plume of CO₂-rich formation water during CO₂ injection. Finally, the applicability of the laboratory assembly for measuring reliable retention curves of unconsolidated sedimentary rocks will be further tested in the near future.

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