

NUMERICAL INVESTIGATION OF TEMPERATURE EFFECTS DURING THE INJECTION OF CARBON DIOXIDE INTO BRINE AQUIFERS

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ABSTRACT

The development of sophisticated numerical modeling capabilities for the simulation of carbon dioxide injection into geological formations is currently an intensive field of research. We have developed a non-isothermal two-phase two-component model concept which is capable of simulating the CO₂ plume evolution, the solution of CO₂ in water and the variation of the fluid properties depending on the thermodynamic conditions and the phase compositions. Since the model also accounts for the balance of thermal energy, we can investigate numerically the effects of temperature variations during injection scenarios. The effects are investigated by means of a principle parameter study and a complex reservoir scenario.

1. INTRODUCTION

Recent investigations of underground carbon dioxide storage are increasingly supported by numerical modeling. The development of multi-phase multi-component models that are capable of simulating the strongly coupled non-linear flow and transport processes has made significant progress, cf. for example [?, Class et al., 2002, Bielinski, 2006], such that these tools provide valuable help for addressing the vast number of open questions. These concern risk analysis, feasibility (technical and economical), and in particular the improved understanding of the physical processes. A number of research projects worldwide are currently going on where numerical simulations give significant contribution. The authors are involved in several projects funded by the European Union (project CO2SINK), the German Research Foundation - DFG - and the German Federal Ministry of Education and Research - BMBF - (projects BENCHMARKS, CO2TRAP within the research program GEOTECHNOLOGIEN).

Obviously, the interest during CO₂ injection into a geological formation focuses on the development of the CO₂ plume and the migration paths of the fluid through the subsurface. It is important that the trapping of the carbon dioxide works sustainably while the mechanisms can be very different. It can be distinguished between hydrodynamic, residual, solubility, and mineral trapping. Therefore, depending on the questions sought to be answered with respect to the trapping mechanisms, the model concept underlying the numerical simulators has to be chosen accordingly and can get very complex. The model that was developed in our group by [Bielinski, 2006] takes into account the flow and transport of the two phases CO₂ and water/brine with mutual solubility, non-isothermal

effects, and the variation of the CO₂ fluid properties like density, viscosity, and enthalpy over a large range of sub- and supercritical thermodynamic conditions.

Another aspect of the subsurface processes during CO₂ injection is the temperature evolution in the formation. The behavior of the local temperature depends on several factors like the enthalpy of the injected CO₂, the heat capacity and heat conductivity of the formation and the expansion of the fluid which is coupled with a temperature lowering (Joule-Thomson cooling). In the following, we present a principle numerical investigation concerning these effects and a complex reservoir simulation motivated by the work within the CO2SINK project.

2. PARAMETER STUDY IN A RADIAL SYMMETRIC DOMAIN

A simulation scenario is set up to study non-isothermal effects in the subsurface during CO₂ injection and to investigate the possibility of using these temperature variations as a means to monitor the CO₂ plume propagation. The model domain is set up using simplified characteristics of the Stuttgart Formation addressed in the CO2SINK project (cf. Sec. 3). The CO₂ is assumed to move away from the injection well in a radially symmetric manner, the target formation has a thickness of 30 m, and the overlying caprock is modeled as a no-flow boundary condition. The injection rate is $1 \left[\frac{kg}{s} \right]$ and takes place over the lower 5 m of the formation. Two main uncertainties are input to the simulations, namely the temperature of the carbon dioxide at the injection point and the permeability of the reservoir. Therefore, a range of CO₂ injection temperatures and various permeabilities are covered within numerous simulations to be able to estimate the non-isothermal effects that can be expected in reality.

Figure 1 (left) shows the CO₂ propagation in the formation illustrating saturations. Also two observation wells 50 m and 100 m away from the injection point are shown. The temperatures at the first observation well (50 m distance from the injection point, right underneath the caprock) are shown over time in Figure 1 (right) for various cases. Cases 1-3 correspond to low (40 [°C]), cases 7-9 to high (60 [°C]) CO₂ injection temperatures. Furthermore, the permeabilities vary between 30 [mD], 300 [mD], and 1000 [mD] to account for the lack of data.

The characteristics of the temperature behavior at the observation well are similar for all cases: as soon as the CO₂ front reaches the location of the temperature sensor, a temperature decrease of 1-2 [°C] can be observed. This cooling is caused by the expansion of the fluid after entering the formation (Joule-Thomson cooling). In the further course of the simulation the temperature at the observation well increases towards the corresponding CO₂ injection temperature. Heat conduction into the formation keeps the temperature at the observation point below this value.

The discussed simulations suggest that temperature measurements can be used to monitor CO₂ plume propagation. However, more detailed investigations are to be carried out and to be published soon.

3. COMPLEX RESERVOIR SIMULATIONS

The complex reservoir model is set up from data out of the CO2SINK projekt. The objective of this project, supported under the FP/6 framework by the EU commission, is to monitor CO₂ injection in a saline aquifer in the North German Basin (30 km west of

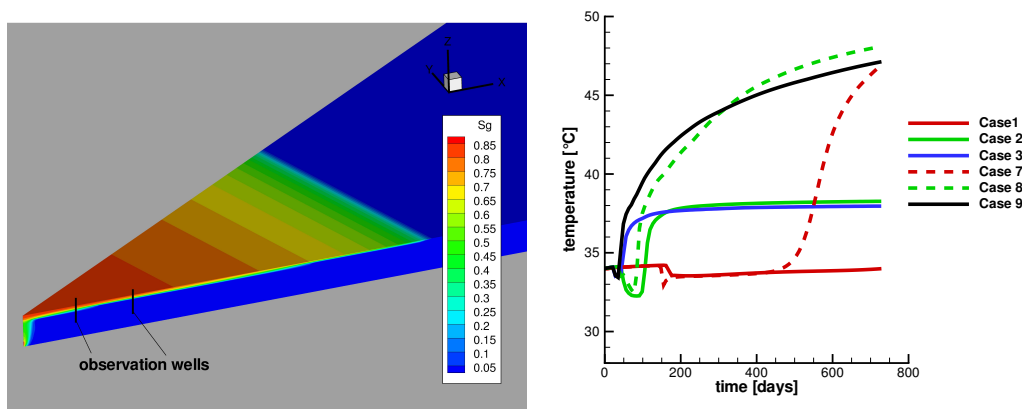


FIGURE 1. Non-isothermal effects during CO₂ sequestration in the subsurface. Model domain and observation wells (left). Temperature evolution at first observation well right underneath caprock (50 m distance from injection point).

Berlin). The target formation, the Triassic Stuttgart Formation, forms a double anticlinal structure at around 570-900 m depth at the selected site. It is planned to inject a total mass of up to 60.000 tons carbon dioxide within two years time. The CO₂ plume evolution, temperature and pressure effects will be monitored with various methods via the injection well itself, two observation wells and from the surface. Once this data is collected, it provides a possibility to history-match a complex reservoir model. This is the first set-up of the reservoir model, which will get further developed with increasing availability of data. At present, all the data available about the properties of the target reservoir were collected by core analysis of a single well in the eastern Ketzin anticline and extrapolation of seismic data in addition to regional studies. Seismic investigations have also been conducted. In this first model only the target formation will be considered. The top and bottom boundaries are modelled as Neumann (no-flow) boundary conditions. At the lateral boundaries, Dirichlet conditions with hydrostatic brine pressure and geothermal temperature condition are assumed. The brine salinity is set to be 250 [$\frac{g}{l}$]. The geothermal gradient was derived to be ~ 0.04 [$\frac{^{\circ}C}{m}$]. The fluid properties over depth calculated from this pressure and temperature gradients and salinity can be seen in Figure 2. For detailed information about functions used, see [Bielinski, 2006] or [Ebigbo et al., 2006].

The overall model extent is 5 km · 5 km · 80 m (Volume = 2 [km³], Porevolume (PV) = 0.4 [km³]). With an assumed average CO₂ density of 360 [$\frac{kg}{m^3}$] the injected CO₂ is 0.054 PV in total. In earlier studies we determined a required minimum distance between injection well and Dirichlet boundary conditions (for this injection rate) to prevent those boundary conditions from dominating the problem.

A permeability model of the Stuttgart Formation was built, using a geostatistical modelling approach after [Deutsch and Wang, 1996]. All well and seismic data available were taken into account. Förster et al. [Förster et al., 2006] describe in detail the geological modelling. One randomly selected realization of the resulting permeability distribution can be seen in Figure 3. The porosity is set to 0.2 [-].

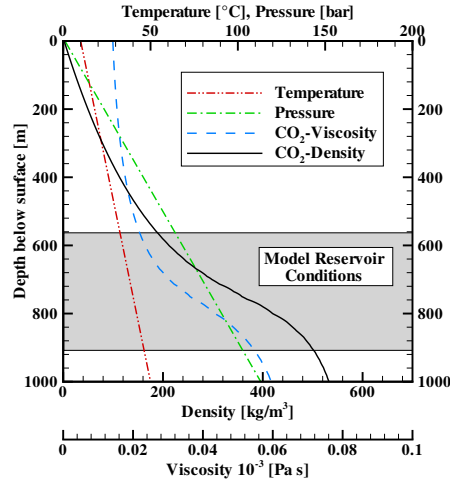


FIGURE 2. Natural pressure and temperature conditions of the reservoir and calculated CO₂ density and viscosity.

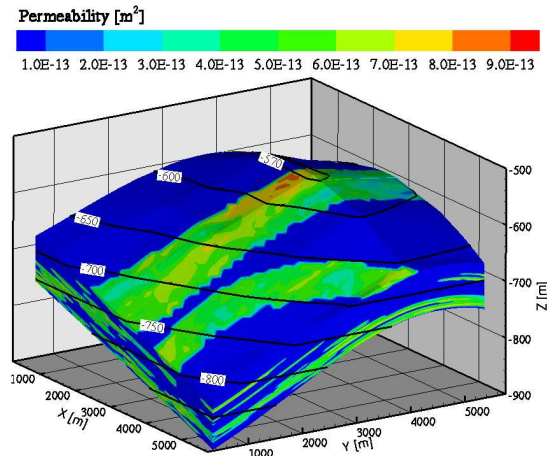


FIGURE 3. Model domain of the complex reservoir: Shown is one realization of the permeability distribution. Highly permeable sand-channel facies lie within a matrix of low permeable floodplain deposits.

The model results presented here, were obtained using one selected realization using this geostatistical approach and does therefore not provide predictions of the plume evolution and overpressures to be expected. Further studies are necessary to give estimates of reliability and error. This work is currently being carried out.

Initial values are the same pressure and temperature gradients assumed for the lateral boundaries. The aquifer is initially fully brine saturated with a mass content of $10^{-4} \left[\frac{kgCO_2}{kgbrine} \right]$ due to numerical reasons. For the relative permeability and the capillary pressure-saturation relationships a Brooks-Corey approach [Brooks and Corey, 1964] is chosen, using best guess values due to lack of data ($p_d=10.000$ [Pa], $S_{wr}=0.1$, $S_{CO_2r}=0.05$, $\lambda=2$). Measurements to determine such values will be conducted once the injection and

the observation wells are drilled and core samples have been taken. At the bottom boundary in the middle of the domain a constant massflux of $1 \left[\frac{kg}{s} \right]$ supercritical CO_2 with a constant temperature of $46 [^{\circ}C]$ is injected over a period of 2 years. The saturation distribution calculated with this realization after 2 years and 5 years after injection start is shown in Figure 4.

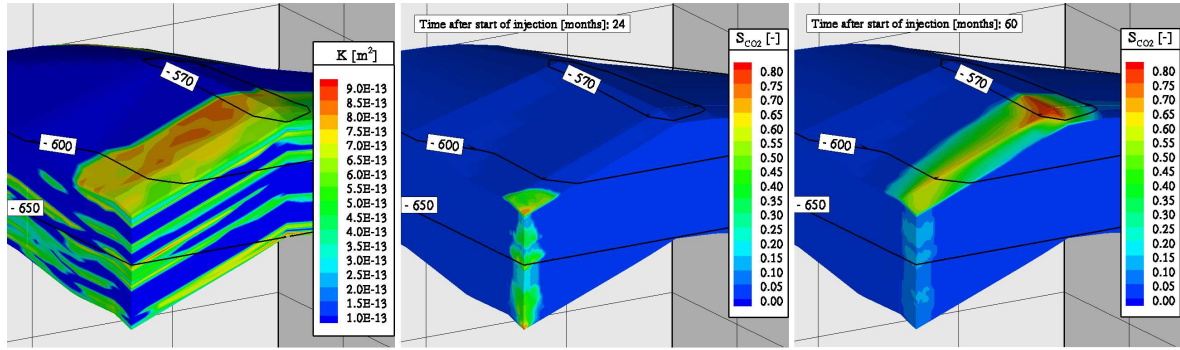


FIGURE 4. Cut-open top-quarter section of the reservoir. Shown is the permeability (left), CO_2 saturation after 2 (middle) and 5 years of injection. Injection shut-in is after 2 years.

The plume evolves starting from the point of injection at the bottom of the domain. Within 14 months the CO_2 reaches the caprock. The lateral spreading is maximum 160 meters away from the vertical injection axis. It can be clearly seen that the CO_2 accumulates in the low permeable regions. It quickly migrates through the high-permeable regions, due to strong buoyant forces. In this regions the saturation is low. After 37 months the highest point of the reservoir is reached. Over time the CO_2 accumulates there and saturations of 0.8 are calculated just underneath the caprock after 5 years. In Figure 5 the corresponding temperature obtained can be seen.

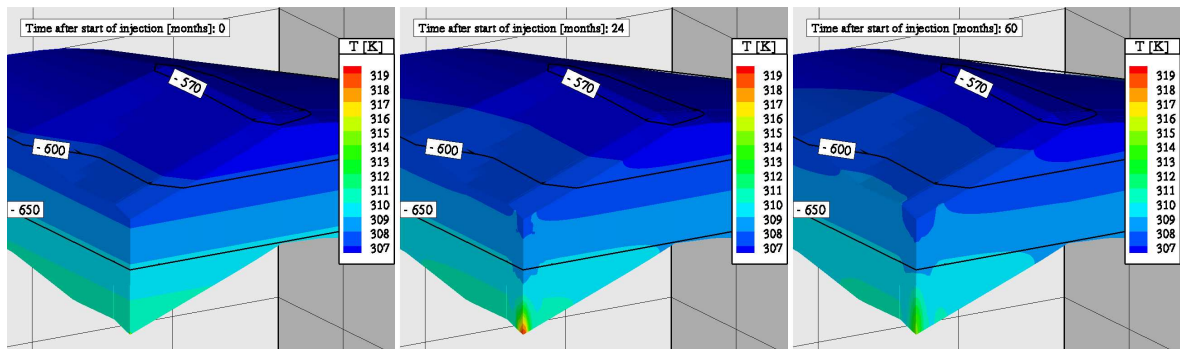


FIGURE 5. Cut-open top-quarter section of the reservoir. Shown is the temperature in the reservoir after 2 (left) and 5 years of injection. Injection shut-in is after 2 years.

The CO_2 is injected with a constant temperature of $46 [^{\circ}C]$, this has a strong influence on the developing temperature field. The reservoir gets heated around the injection point up to the temperature of the injected CO_2 . In the higher regions above the injection

point, a maximum temperature decrease of $0.6 [^{\circ}C]$, with respect to the initial reservoir temperature, after 2 years can be observed. This is due the previously explained expansion of the CO_2 due to pressure drop (Joule-Thomson effect).

After 5 years the region just around the injection point, which has been heated up, slowly normalises back to initial temperature conditions. The cooling effect above this region is still strong, there is no indication for a normalisation back to initial conditions even 3 years after injection shut-in. No temperature effects can be observed at the top of the reservoir, where the CO_2 finally accumulates.

4. FINAL REMARKS

In this paper, we presented two 3D numerical simulation examples concerning non-isothermal effects during CO_2 injection into brine aquifers. We could show and identify the physical processes that produce temperature variations in the near-field of the injection well. The area of influence is apparently restricted to the vicinity of the well and the effects may be negligible in many cases. However, there can be scenarios where high temperature changes due to sudden expansion of the CO_2 occur. We think of fault zones, fractures, and abandoned wells with locally very high permeabilities compared to the surrounding reservoir. Thus, it is necessary to investigate this in more detail. We refer here to the work of [Ebigbo, 2005] and the project BENCHMARKS within the German GEOTECHNOLOGIEN program [GEOTECHNOLOGIEN, 2005]. The authors acknowledge the EU, DFG, and BMBF for their funding which contributed to this work.

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