

Aquifer storage capacity of CO₂

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Abstract

CO₂ storage is a recognized measure to combat the global warming. One of the most promising methods is subsurface storage in aquifers. CO₂ storage location choice is mainly governed by the properties of rock and aquifer fluid. A computer code has been developed to assess CO₂ aquifer storage. With this code a sensitivity study has been performed of aquifer CO₂ storage capacity as a function of the aquifer depth, geothermal gradient and aquifer brine salinity.

Keywords: CO₂, aquifer, storage, capacity

Introduction

For planning purposes assessment of the local aquifer CO₂ storage capacity is a big issue. A set of general physical properties is needed for this assessment, depending on pressure, temperature and aquifer salinity (P-T-S) as CO₂ density, water density, CO₂ solubility in water and water compressibility. Also a set of location dependent properties are needed: the geothermal gradient (GG), leak off pressures (a measure for maximum fluid injection pressure), the aquifer salinity and aquifer matrix compressibility. Influence of these properties on storage capacity has been calculated using the developed code. As an example the CO₂ aquifer storage capacity for a hypothetical aquifer offshore The Netherlands is presented.

The storage capacity calculation procedure

It can be expected the pore volume of an aquifer is 100% filled with water and the fluid pressure to be at hydrostatic conditions. Consequently any fluid injection in an aquifer is only possible by compression of the pore water and of the aquifer formation at pressures higher than hydrostatic. An extra injection effect favorable for storage is the dissolution of CO₂ in pore water. So storage capacity assessment consists of calculating the storage effects of compression and dissolution processes under variable pressure, temperature and salinity conditions.

For this purpose a computer code has been developed incorporating these physical processes and all necessary system properties. The code allows to perform a quick scan to get some insight in the optimal CO₂ storage site and optimal depth. Taking into account realistic ranges of storage site parameters a sensitivity study has been performed to show the capabilities of the quick scan tool, using hypothetical aquifers with fixed values of thickness = 150 m; porosity = 0.22 and net /gross quotient = 1.0. The ranges of the variable properties relevant for the CO₂ aquifer storage are: mean aquifer depth: 0 - 3000 m-sl; geothermal gradient (GG): 0.020 – 0.045 °C/m and aquifer salinity (S): 0 – 25 weight percent. The aims of the calculations are the CO₂ mass that can be stored per km² in an aquifer and the pore space efficiency. All system properties are expected to be time-invariant except the CO₂ dissolution. For the injection period (some 30 years) the CO₂ storage by dissolution is taken to be only 10% of its capacity, which is the typical amount of dissolution observed in reservoir modelling simulations such as SIMED (e.g. Van der Meer, Van Wees and Nepveu, GHGT8). This can be explained by the specific behavior of CO₂ directly after injection: Due to buoyancy effects the injected CO₂ has the tendency to rise to the top of the aquifer in the direct vicinity of the injection well immediately after injection and subsequently to spread underneath the aquifer seal. This process characteristic indicates a minor contact of CO₂ and aquifer water in short term. In the following the main system properties are presented and discussed, generated from recent sources.

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Properties of CO₂

In this section the CO₂ density is presented followed by the CO₂ solubility. Some years ago a new equation of state of CO₂ was presented by Span and Wagner^[1]. This is the source of the algorithm of the US National Institute of Standards (NIST) for the calculation of the CO₂ density.

CO₂ density

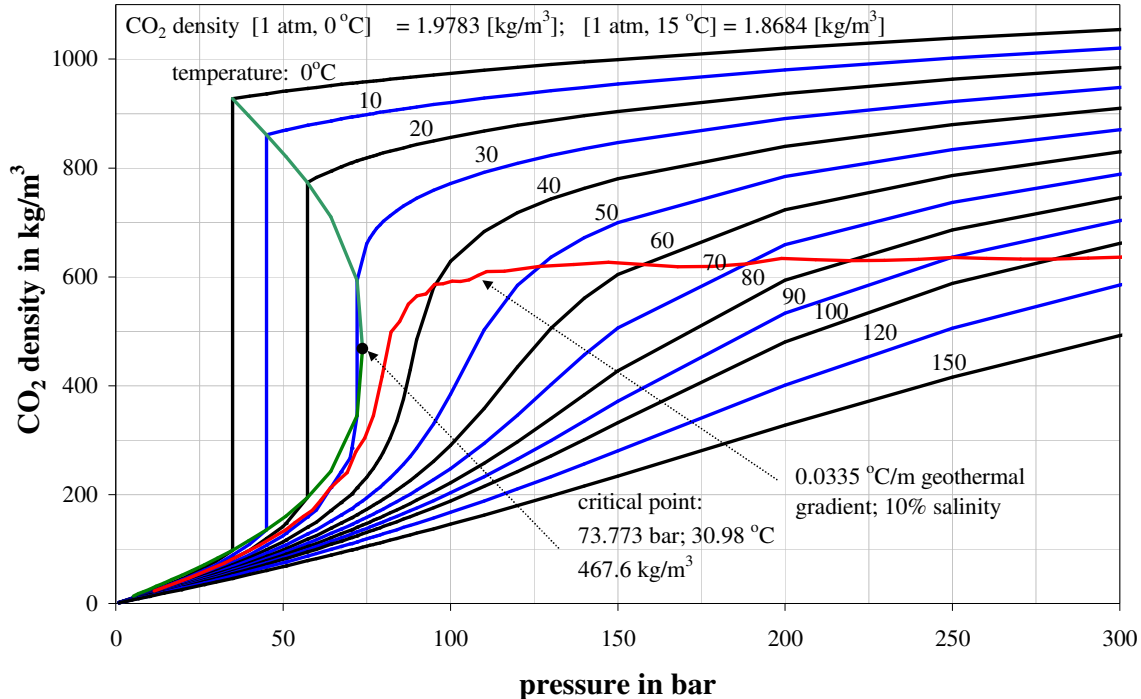


Figure 1 CO₂ density as a function of P-T (blue and black curves), after Span and Wagner, 1996 (NIST, 2004). The green curve connects jumps at certain P-T points. The red curve shows an example of the CO₂ density trend with depth.

The change of density of pure CO₂ with pressure or temperature is calculated using this NIST algorithm. The results are shown in Figure 1. The behavior of the CO₂ density between the triple point (P-T = 5.18 bar, -58.56 °C) and the critical point (P-T = 73.77 bar; 30.98 °C) is special. In this

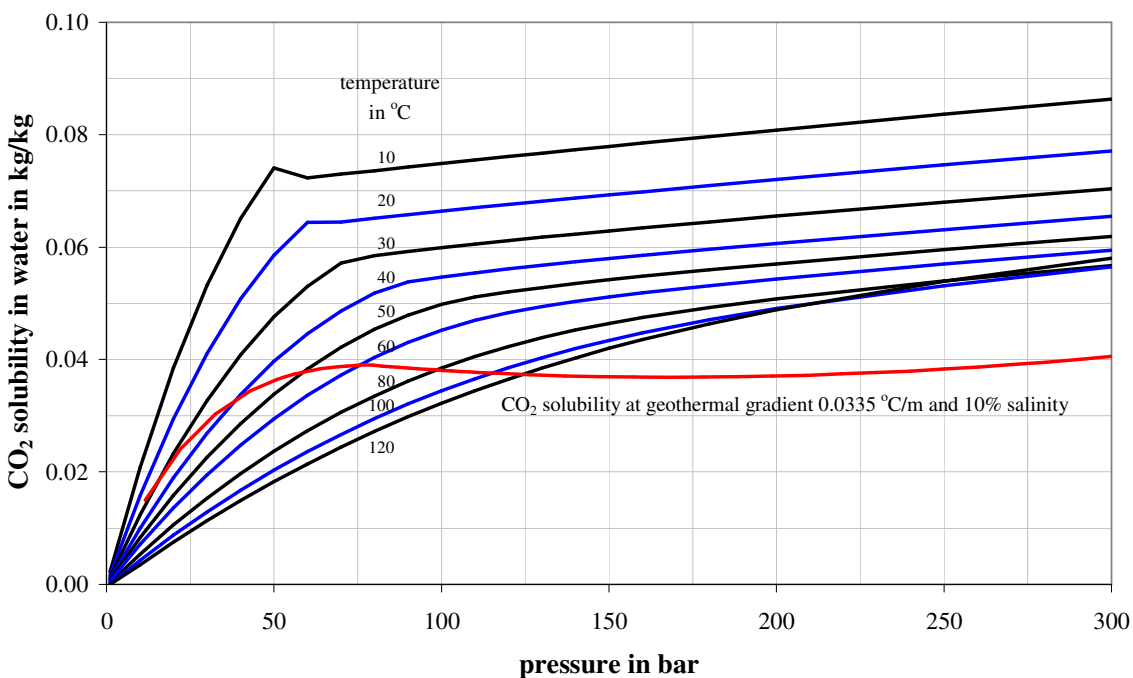


Figure 2 Calculated solubility of CO₂ in pure water as a function of P-T (blue and black curves), based on Duan and Sun (2003). The red curve shows an example the CO₂ solubility trend with depth. unstable P-T-range the CO₂ density value shows a jump for certain P-T-combinations. This jump implies a state change from gas to liquid (low to high density) or reverse. This jump from gas to liquid state is observed at the RECOPOL CO₂ injection site in Poland (Personal communication with Frank van Bergen, August 2004).

Solubility of CO₂ in water

Duan and Sun^[2] recently published a new approach for computing the solubility of CO₂ in water based on a new equation of state. They presented a method to calculate the dissolution of a gas in water for suitable P-T-S ranges. Fig. 2 shows the CO₂ solubility in pure water, generated with the Duan&Sun algorithm. It can be concluded from the generated solubility values for the P-T-S range of interest that the solubility of CO₂ decreases with increasing water salinity. This effect is shown in Table 1. The numbers are averaged values for P-T ranges of 1 to 300 bar and of 10 to 100 °C.

| water salinity in NaCl percentage | solubility fraction compared with pure water solubility | standard deviation due to P-T-variation |
|-----------------------------------|---|---|
| 0 | 1.000 | - |
| 5 | 0.838 | 0.012 |
| 10 | 0.709 | 0.020 |
| 15 | 0.609 | 0.032 |
| 20 | 0.525 | 0.031 |
| 25 | 0.453 | 0.045 |

Table 1 Averaged reduction of CO₂ solubility in water at increasing aquifer salinity

Enforcing storage space by compression

In the sequel the maximum allowable injection pressure and fluid storage by aquifer compression are discussed. Generally the storage space must be enforced by an injection pressure exceeding hydrostatic pressure. This overpressure compresses the pore water and the aquifer matrix.

Maximum allowable pressure

Imposing aquifer overpressure by fluid injection is equivalent to overpressuring the rock pore fluid. This causes the enlargement of pore space and implicitly compression of the aquifer matrix. Another effect of the pore overpressure is the compression of the pore water. These two compression effects together supply storage space for the fluid to be stored, like CO₂. *So the key questions for fluid storage in aquifers are the aquifer volume that is subdued to any pressure increase by fluid injection and the allowable maximum injection pressure.* Van der Meer^[3] investigated leak off pressures (LOP) of drilled wells offshore The Netherlands. His results are summarized by: The LOP is 1.35 times the hydrostatic pressure (HP) for depths lower than 1000 m-sl, 2.4 times HP for depths larger than 5000 m-sl with a linear trend for factor increase for depths in-between.

Water compression

Nunere^[4] expressed the compressibility of brine in a correlation with P-T-S. Some numbers: the water compressibility is about $4.75 \cdot 10^{-5}$ 1/bar for a range from 25 – 100 bar. The water compressibility is reduced at higher water salinity. The reduction factor ranges from 0.90 for 5% to 0.60 for 30% water salinity.

Pore space enlargement

The relation between drained bulk rock compressibility C_{BC} and pore compressibility C_{PP} is developed by Zimmerman^[5] using the following relationship: $C_{PP} = [C_{BC} - (1 + \emptyset)C_r] / \emptyset$. In this expression \emptyset is the rock porosity and C_r the compressibility of the intact rock. For the calculation example offshore The Netherlands the compressibility values of Berea sandstone have been used. This

C_{PP}-C_{BC}-overpressure relationship is built into the computer code. For Berea Sandstone it can be expected the pore compressibility decreases from $3.5 \cdot 10^{-4}$ 1/bar with a factor 0.86 to 0.36 to 0.17 for overpressures of 10 to 50 to 100 bar.

Results

Example calculations

The main results are shown in Figure 3 as an example for a situation offshore The Netherlands. The CO₂ density and the CO₂ dissolution storage values show a maximum value for larger depths. These phenomena have been found for all calculations.

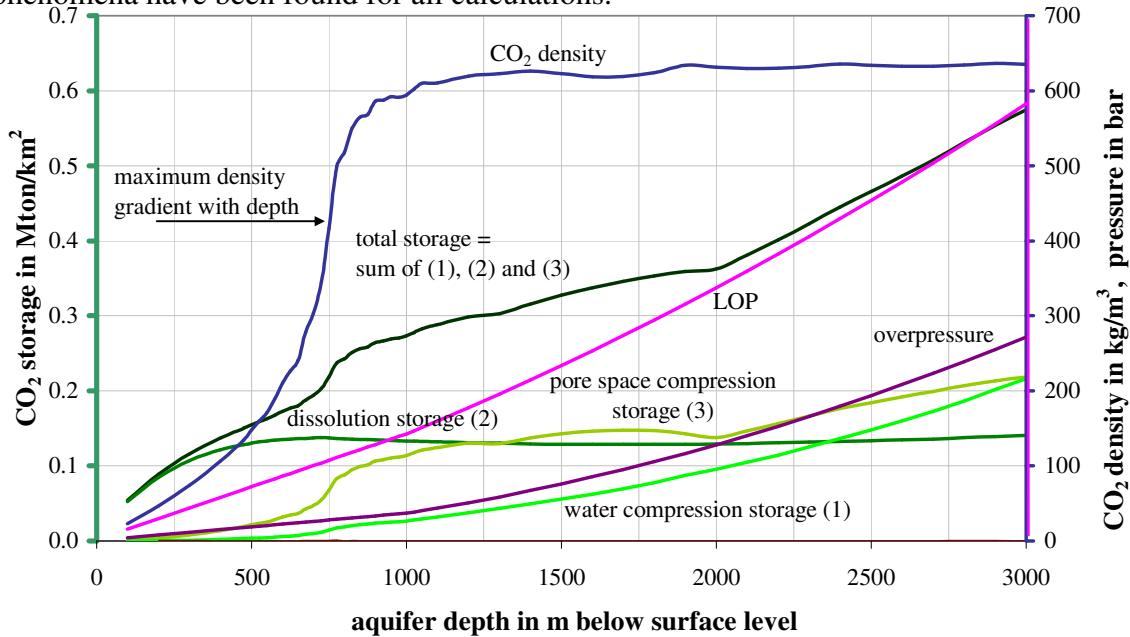


Figure 3 Components of CO₂ storage in an aquifer (1), (2), (3); CO₂ density, leak off pressure (LOP) and pore fluid overpressure as a function of mean aquifer depth for a GG-S of 0.0335 °C/m, 10%.

Results of the sensitivity calculations

The calculations of depth depending CO₂ aquifer storage capacity values have been performed for geothermal gradient values ranging from 0.020 to 0.045 °C/m and the aquifer salinity ranging from 0 up to 25%. For the optimal storage depth arbitrarily the depth is chosen at which the CO₂ density gradient with depth is at maximum plus 100 m.

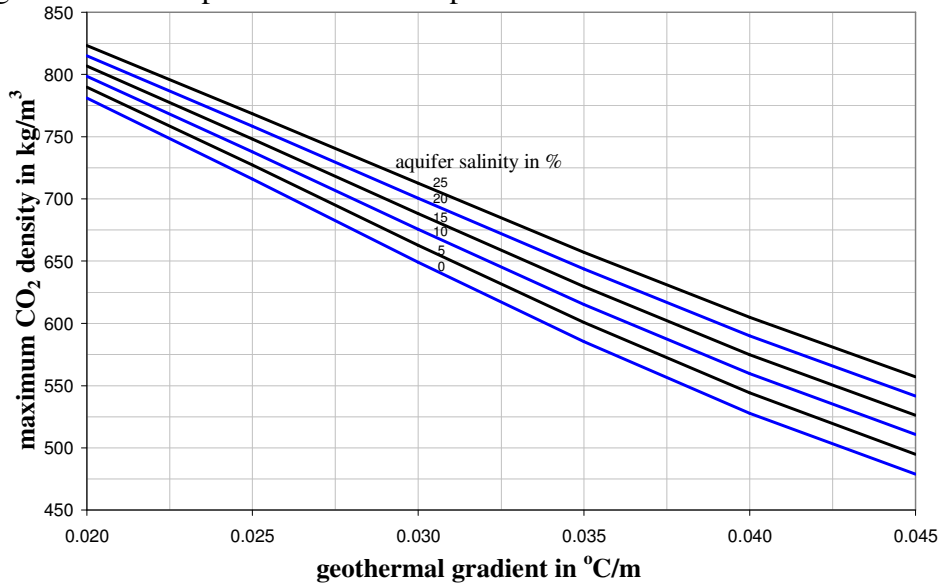


Figure 4. The maximum of CO₂ density values in trends with depth as a function of the geothermal gradient and aquifer salinity

Maximum values of CO₂ density and CO₂ dissolution in trends with depth

The CO₂ density shows a maximum for larger depths due to counteracting tendencies at increasing depth: an increasing density with pressure and a decreasing density with temperature (see Figure 1). This CO₂ density maximum as a function of the geothermal gradient and aquifer salinity is shown in Figure 4. The solubility of CO₂ in water in trends with depth also shows a maximum for larger depths. In Figure 5 these solubility maxima are shown for different geothermal gradients and aquifer salinities. The explanation is conform the CO₂ density maximum (see Figure 2).

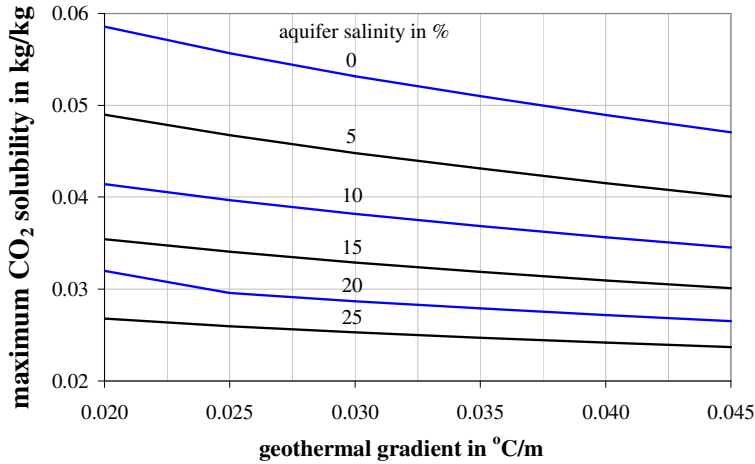


Figure 5 The maximum values of CO₂ solubility in water in trends with depth as a function of the geothermal gradient and aquifer salinity

CO₂ aquifer storage capacity

The results of CO₂ aquifer storage capacity show a general decrease with increasing geothermal gradient and with increasing aquifer salinity (Figure 6). These tendencies are the result of the tendencies of CO₂ density, of CO₂ solubility, of the depth of maximum CO₂ density gradient and of aquifer compressibility with geothermal gradient and aquifer salinity (see figure 3).

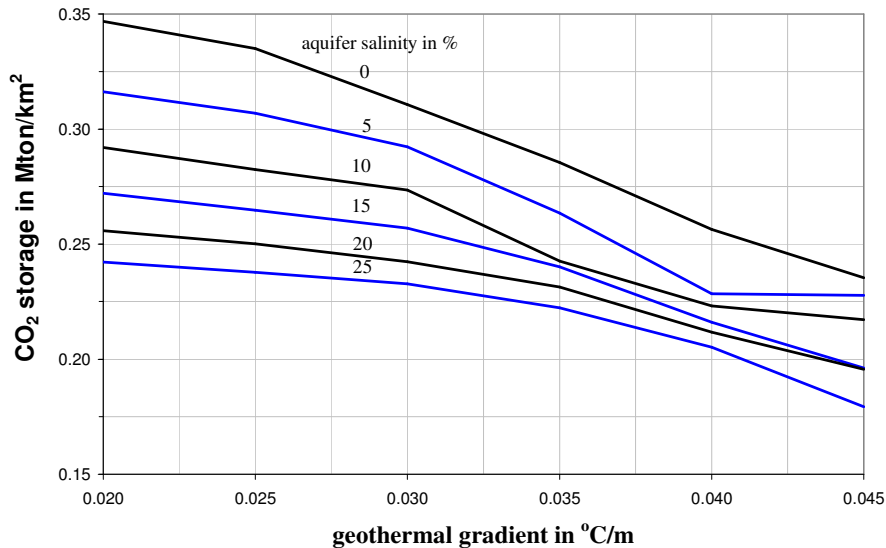


Figure 6 Storage capacity of CO₂ in Mton/km² as a function of the geothermal gradient and of the aquifer salinity due to maximum allowable pressurizing of an optimal positioned example aquifer.

Pore space storage efficiency

The CO₂ storage efficiency as discussed in the paper of Van der Meer ^[6], ranges from 1 to 6 effective pore space percentage (PS%) depending on the vertical transmissivity of the aquifer. In Figure 7 the calculated storage efficiency is shown as a function of the geothermal gradient and aquifer salinity for an aquifer at optimal depth.

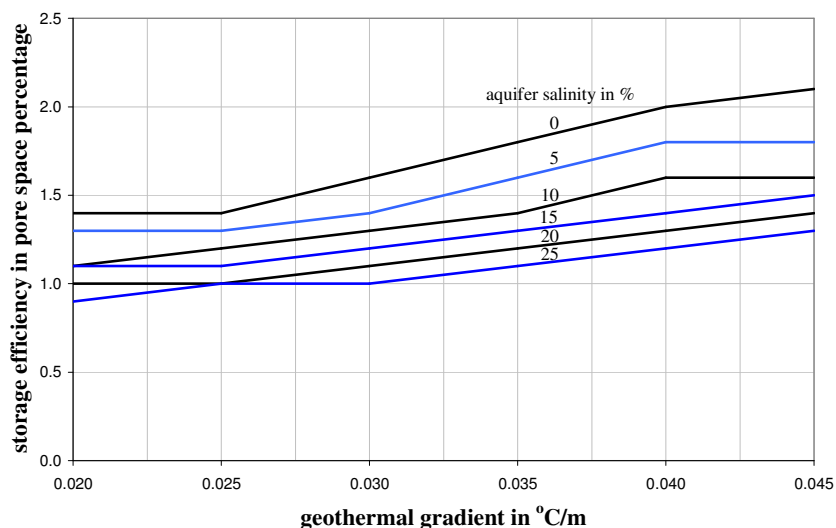


Figure 7 CO₂ storage pore space efficiency as a function of geothermal gradient and aquifer salinity due to maximum allowable pressurizing of an optimally positioned example aquifer.

Conclusion

The capacity of aquifer CO₂ storage is sensitive to both the geothermal gradient and the pore water salinity. The storage site with a low geothermal gradient and a low aquifer salinity is preferable. Remarkable phenomena are the maximum CO₂ density values in trends with depth and the maximum CO₂ solubility values in trends with depth. The main unknown in case of fluid storage by aquifer compression is the aquifer volume that is subdued to any pressure increase by fluid injection and the allowable maximum injection pressure.

Discussion

For the applied overpressure in the calculations the leak off pressure has been taken (see Figure 3). In reality the allowed overpressure will be restricted to modest values as the capability of the aquifer seal to withstand overpressure is not known. The dynamic injection well overpressure will be dominant for safety assessment of the aquifer seal. Another restriction of storage capacity is the porosity reduction with depth. This shows an exponential decrease. Taking into account both influencing factors will lead to shallower CO₂ storage optima and lower capacities.

References

- [1] Span, R and Wagner, W. A new equation of state for carbon dioxide covering the fluid region from the triple point to 1100 K at pressures up to 800 MPa. *J. Phys. Chem. Ref. Data*, 1996;25:1509-1588.
- [2] Duan Z, Sun R. An Improved Model Calculating CO₂ Solubility in Pure Water and Aqueous NaCl solutions from 273 to 533 K and from 0 to 2000 bar. *Chemical Geology* 2003;193:257-271.
- [3] Van der Meer LGH. Reservoir technische aspecten. In: Wildenborg AFB, Breunese JN, Van der Meer LGH. *Potentieel voor CO₂-opslag onder het Nederlandse deel van het Continentale Plat*. NITG 98-177-B, p. 34
- [4] Numbere D, Brigham WE, Standing MB. *Correlations for physical properties of petroleum reservoir brines*, Petroleum Research Institute, Stanford University, 1977
- [5] Zimmerman RW. *Compressibility of Sandstones*. Elsevier 1991, Amsterdam.
- [6] Van der Meer LGH. The CO₂ storage efficiency of aquifers. *Energy Conserv. Mgmt.*, 1995. 36:513-518.