Interwell field test to determine in-situ CO$_2$ trapping in a deep saline aquifer: Modelling study of the effects of test design and geological parameters

Fritjof Fagerlund$^{a,*}$, Auli Niemi$^a$, Jacob Bensabat$^b$, Vladimir Shtivelman$^c$

$^a$Uppsala University, Villavägen 16, 75236 Uppsala, Sweden
$^b$Environmental & Water Resources Engineering, Haifa, Israel
$^c$Geophysical Institute of Israel, Lod, Israel

Abstract

An interwell field test to determine residual phase and dissolution trapping of CO$_2$ is being designed at Heletz, Israel. Effects of test-design options and geological parameters were investigated using numerical modelling. It was found that the interwell distance has large influence on the feasibility of the test both in terms of creation of a zone of residually trapped CO$_2$ and detection of the time when such zone has been created. The optimal distance is site-specific and depends on formation properties. Alternating CO$_2$ and brine injections slightly increased residual trapping, but did not facilitate creation of a well-defined zone of trapping.

© 2013 The Authors. Published by Elsevier Ltd. Selection and peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: CO$_2$ geological storage; field test; residual trapping; dissolution; interwell test

1. Introduction

Carbon dioxide (CO$_2$) capture and storage (CCS) is a potential key contributing technology for reducing greenhouse gas (GHG) emissions to the atmosphere [1],[2]. Efficient implementation of CCS technology requires well-characterized storage formations capable of trapping the injected CO$_2$ over a long period of time, thus providing safe storage of the CO$_2$ with respect to humans and the environment.

* Corresponding author. Tel.: +46-18-471-7166; fax: +46-18-551124.
E-mail address: fritjof.fagerlund@geo.uu.se.
Trapping of the CO$_2$ occurs under low-permeability, high-entry-pressure cap rock layers, but is further enhanced by other trapping mechanisms which are particularly important if the storage formation has an open boundary, if a spill point exists in the cap rock or if leakage occurs. Residual phase trapping together with dissolution of CO$_2$ in groundwater are key secondary trapping mechanisms, which are essential for storage security in open CO$_2$ storage formations and critical for the attenuation of any leaked CO$_2$.

Residual phase trapping has typically been measured in connection with capillary pressure measurements at the core scale, while on larger scales, experimental data are generally lacking. Field tests to measure trapping in situ are currently being designed [3], but much uncertainty remains in quantifying and predicting residual phase trapping in relevant CO$_2$ storage formations. Qi et al. [4] argue that the strategy for CO$_2$ injection has a large impact on residual phase trapping, and suggest that water should be co-injected with the CO$_2$ to maximize trapping. Dissolution of CO$_2$ increases the density of brine which can produce a density-driven convective mixing and thereby increase the rate of dissolution as compared to the diffusion-limited case [5]. However, much uncertainty remains about the dissolution process at actual CO$_2$ storage sites and which are the critical parameters controlling the dissolution rate in the field.

It can be concluded that field tests are critically needed to measure the amount of CO$_2$ which is effectively trapped in-situ, evaluate parameters that influence the trapping over larger scales and under influence of geological heterogeneity. Thereby fundamental knowledge to understand the trapping processes at the field scale can be gathered and a foundation to build and validate large-scale trapping models can be obtained. At Frio, Texas, the migration of a small CO$_2$ injection in a deep saline aquifer was monitored from an updip well by a combination of techniques including fluid sampling, well logs and cross-hole seismics [6]. Similarly, at the Ketzin site, Germany, CO$_2$ injections have been monitored from three boreholes using geophysical, hydraulic and tracer techniques [7],[8]. These studies underscore the importance of combining several different measurement techniques with a site model for CO$_2$ migration to analyze and understand the flow and transport processes in the deep subsurface.

Tests particularly aimed at measuring the trapping of CO$_2$ in the field remain very scarce. At Otway, Australia a single-well field test was designed to measure residual phase trapping using a push-pull CO$_2$ injection-withdrawal scheme [9]. Further small-scale field tests aimed at characterizing and quantifying CO$_2$ trapping processes are being designed within the EU-FP7 MUSTANG project at the Heletz site, Israel. Here, an interwell test, with CO$_2$ injection in one well and active withdrawal of fluids from a second well, is a new concept for simultaneous measurements of residual phase and dissolution trapping.
in-situ, which was recently presented by Fagerlund et al. [3]. A schematic figure of such test is shown in Fig. 1a. Active withdrawal from the one well (W) allows sampling and analyses of extracted fluids and tracers as well as control of the fluid flow field. A combination of several measurement techniques, including hydraulic, tracer, thermal and geophysical tests, can be used to measure the trapping that occurs as the CO2 migrates through the formation between the two wells.

The general outcome and success of the interwell test depend on design options such as the distance between the wells and the injection/withdrawal rates and volumes, and also on site-specific geological parameters such as permeability, trapping parameters and heterogeneity. While the concept, methodology and general feasibility of the proposed interwell test has been shown [3], the effects of different geological conditions and design options need to be further investigated to obtain a better understanding about how this test should be performed at a given site and which factors control the optimal design. The aim of this study was to use numerical modelling to investigate how these design options and geological parameters affect the flow and transport processes in the formation and outcome of the test. In particular, the objectives were to address the following key questions related to the test design:

- How does the interwell distance affect the outcome of the test?
- How should a suitable injection-withdrawal scheme be designed?
- How do the properties of the storage formation affect the test?

The feasibility of the interwell test depends e.g. on the amount of dissolution and residual trapping that occur, the pressure build-up in the formation and the time required to achieve complete trapping and perform the tests. Furthermore, the accuracy of the test depends on the ability of the different measurement techniques to quantify the trapping under different conditions. In particular, critical aspects include that: (i) the system state when the supercritical (sc) CO2 is residually trapped can be identified, (ii) effective residual scCO2 saturation can be measured (a larger amount of trapped scCO2 is advantageous, still mobile scCO2 present when measurements are taken can produce error), (iii) in-situ dissolution can be measured (shown to be feasible using low soluble tracers in the scCO2 phase given a stable dissolution rate and flow field [6]), (iv) time to reach state of residually trapped scCO2 is manageable, (v) pressure changes in the formation are manageable.

2. Methods

2.1. Conceptual and numerical model

The conceptual model is based on the target reservoir for CO2 injection at Heletz, Israel. The target formation is a lower-Cretaceous sandstone overlain by a low-permeable cap rock consisting of marls and shale. At the location of the two wells drilled for CO2 injection experiments, the target formation is at a depth of approximately 1600 m and is dipping 7.8°. According to ongoing characterization of the recently drilled wells, the target formation consists of two permeable sandstone sublayers separated by less permeable claystone. The total sandstone thickness is approximately 10.6 m at location of the wells. In the conceptual model used in this study, the target formation consists of two permeable sandstone sublayers separated by less permeable claystone. The total sandstone thickness is approximately 10.6 m at location of the wells. In the conceptual model used in this study, the target formation is simplified as single layer of 10.6 m thickness with an extent that reproduces the total sandstone volume of the closed compartment (2.25 x 10^7 m^3) where CO2 is injected and also approximately the locations of the enclosing faults and formation pinch-out line. Assuming that the target sandstone is homogeneous, there is symmetry over the line of maximum dip and the formation can be modelled as one symmetrical half of the total domain with the two wells along the line of maximum dip which also constitutes the symmetry boundary (Fig. 1b). The Northern Heletz compartment where CO2 injection will take place is described in more detail by Fagerlund et al. [6] who also used a similar conceptual model. The geology of the site relevant to CO2 storage has been described in more detail by Erlström et al. [10], [11].
For the numerical modelling of CO₂ injection and two-phase flow of CO₂ and brine in the formation, the multiphase, multicomponent fluid flow and transport code TOUGH2 [12] was used in combination with the equation-of-state (EOS) module ECO2N [13]. The discretization was finer in the region around the wells and a depending on the interwell distance (D) which was different in different modelling scenarios, the total number of gridblocks was between approximately 31000 and 37000 for the 3D symmetrical half model domain (shown schematically in Fig. 1b). The constitutive relationships for capillary pressure (P_c) and relative permeability (k_r) as functions of wetting fluid saturation (S_w) by Brooks and Corey [14] and Burdine [15] were added to the TOUGH2 code and applied in the modelling.

2.2. Injection-withdrawal scheme

The interwell test to determine residual phase and dissolution trapping of CO₂ uses an injection-withdrawal sequence involving two wells, one for injection and one for withdrawal of fluids. The general idea is to first perform reference testing without any CO₂ in the formation, second, create a zone of residually trapped scCO₂, and third, perform the tests again, now with CO₂ at residual saturation present (Fig. 2a). The tests may include e.g. hydraulic, thermal and tracer test as well as geophysics and borehole logging. In the hydraulic test a pulse of water is injected and the pressure response (monitored in both wells) is sensitive to aqueous phase permeability reduction in the presence of scCO₂. In the thermal test the formation is heated and allowed to cool while the temperature at the well depends on heat conduction which is also influenced by the saturation of scCO₂. These tests performed both before and after creation of the zone of residually trapped CO₂ can therefore be used to infer the trapped saturation. Tracers with negligible aqueous solubility in the injected scCO₂ carry information about the dissolution of mobile scCO₂ when scCO₂ is extracted at the withdrawal well. This method of measuring the in-situ CO₂ dissolution is described in more detail by Fagerlund et al. [3]. The base-case injection-withdrawal sequence is shown in Fig. 2a and here for simplicity only includes a hydraulic test (a thermal test and geophysical measurements such as cross-hole seismics would require additional time in the test phases).

![Fig. 2. (a) Injection-withdrawal scheme for the interwell test. (a) Base-case. (b) Injection scheme for alternating CO₂ and water injections (same continuous withdrawal as in the base case).](attachment:figure_2.png)
It can be noted that withdrawal of fluids should be done until most scCO₂ in the formation exists as residually trapped phase, but not longer, because then the residually trapped saturation will start to decrease as a result of dissolution. A critical aspect of performing the test successfully is therefore to be able to identify the point in time when this occurs.

2.3. Modelling scenarios and parameters

To investigate how test-design parameters and the permeability of the target formation influence the outcome and general feasibility of the test, several scenarios were modelled (Table 1). The design parameters include the interwell distance (scenarios 1 – 3) and the active withdrawal of fluids from the withdrawal well (scenarios 6 – 8). Furthermore, the idea of alternating CO₂ and water injections during the CO₂ injection stage was investigated by adding scenarios in which the CO₂ injection was split in 3 parts with 2 water injections in between, as shown in Fig. 2b. The length of the water injections (t_H₂O – defined in Fig. 2b) was varied from half that of the individual CO₂ injections (t_CO₂ defined in Fig. 2b) to double t_CO₂, corresponding to scenarios 9 – 11 in Table 1.

In the CO₂ injection test at Heletz a total injection of 1000 tons of CO₂ is proposed for the interwell test. Here we have assumed that both the injection and withdrawal of fluids can be performed at a rate of 5 tons/hour (= 1.4 kg/s). Thereby the total time of injecting the CO₂ was 8.3 days. With the exception of scenario 4, the withdrawal of fluids was modelled as a constant total extraction rate of 5 tons/hour, which may include both scCO₂ and brine in proportion according to their mobility in the close vicinity of the withdrawal well. For scenario 4 with k = 10 x 10⁻¹⁵ m², the pressure drop in the withdrawal well became too large when trying to maintain a rate of 5 tons/hour. Therefore, for this scenario the withdrawal was modelled as a constant pressure boundary at the well which yielded 5 tons/hour flow during single phase (brine) conditions around the well, but then decreased during the two-phase flow of scCO₂ and brine into the well under reduced permeability conditions.

At the time of performing this study, the final measurements of formation permeability were not available. In both the scenarios with active withdrawal (2, 4, 5) and without withdrawal (6 – 8), the effect
of permeability (k) was investigated by testing different values (k = 10, 50 and 100 x 10^{-15} m^2) within the range of expected k at Heletz based on previous investigations. The range of values also gives information about the general effect of permeability on the feasibility of the proposed test. Porosity (Φ) was linked to permeability based on a general relationship between k and Φ obtained from previously collected core samples of Heletz sandstone. The Brooks-Corey parameters were obtained from the literature based on similar sandstone [16] and scaling of the Brooks-Corey displacement pressure (P_d) as suggested by Leverett [17]. P_d and Φ are given in Table 1. For all scenarios the residual water saturation (S_w) was 0.30, the residual scCO_2 saturation (S_{gr}) was 0.09 and Brooks-Corey λ was 0.762.

3. Results

3.1. Effect of interwell distance and permeability

The spatial distribution of scCO_2 in the vertical plane through the two wells at 71.3 days after start of the test sequence is shown in Fig. 3 for different interwell distances. With active withdrawal (Fig. 3a-c), the scCO_2 flows through the formation and out through the withdrawal well (W). When most of the mobile scCO_2 has been withdrawn, a zone of residually trapped scCO_2 overlain by a thin pancake of mobile scCO_2 exists between the two wells (Fig. 3a and b). With no active withdrawal (Fig. 3d) the migration of scCO_2 is only driven by buoyancy and goes slowly updip (left in Fig. 3).

![Fig. 3. Spatial distribution of scCO_2 in the vertical plane through the two wells at 71.3 days after start of the test sequence for interwell distances (D) of: (a) 30m, (b) 50m, (c) 100m, and (d) with no withdrawal (NWD). k given in mD = 10^{-15} m^2.](image-url)
Both brine and scCO$_2$ are pumped out from the withdrawal well. The flux rate of scCO$_2$ into the well (shown in Fig. 4a) becomes non-zero at the time of scCO$_2$ first arrival. Because a finite amount of 1000 tons is injected but the withdrawal of fluids continues, the scCO$_2$ out flux later starts to decline as less mobile scCO$_2$ remains in the formation. Scenario 4 is not fully comparable to the other scenarios, because due to the low permeability, the boundary condition had to be constant pressure instead of a constant total flux rate (as explained in section 2.3 above), and therefore the total flux decreases as a result of permeability reduction during two-phase flow to the well. When only a thin pancake of scCO$_2$ remains under the ceiling of the storage formation (as illustrated in Fig. 3a,b), the scCO$_2$ flux takes a low slowly declining value, as this last remaining mobile scCO$_2$ slowly flows out of the formation. For scenarios 1, 2 and 5 there is clear transition between a more rapid decline in scCO$_2$ flux rate and this slow-decline regime, which can be seen in Fig. 4a at approximately day 38 for scenario 1 and day 71 for scenarios 2 and 5. For scenario 4, there is no clear transition and for scenario 3 modelling was not performed long enough to reach the time to transition.

![Graph](image)

Fig. 4. (a) Flux of scCO$_2$ to the withdrawal well; (b) Cumulative pumped out CO$_2$ mass. Total CO$_2$ mass is shown with a solid line and the dissolved part only is shown with a dashed line. k given in mD = 10$^{-15}$ m$^2$.

Both scCO$_2$ and dissolved CO$_2$ in the brine contribute to the total cumulative extracted CO$_2$ due to withdrawal of fluids (Fig. 4b). The dissolved CO$_2$ flux rate carries information about the total dissolution in the formation, while tracers with negligible aqueous phase solubility in the scCO$_2$ carry information about the dissolution of mobile scCO$_2$, as explained in more detail by Fagerlund et al. [3]. For a constant total withdrawal rate (all scenarios except number 4 in Fig. 4b), the rate of dissolved CO$_2$ flux to the withdrawal well is relatively constant (constant slope of accumulation). At the end of the simulation period, approximately 80%, 65% and 30% of the injected CO$_2$ had been extracted for the 30m, 50m and 100m interwell distance scenarios, respectively for the case of k = 50 x 10$^{-15}$ m$^2$.

To measure the residually trapped scCO$_2$, a situation when most of the scCO$_2$ in the region between the two wells exists as residually trapped must first be created and identified during the test procedure. At this time the amount of mobile scCO$_2$ still remaining should preferably be small compared to trapped scCO$_2$. Mobile scCO$_2$ decreases with time due to extraction from the withdrawal well, residual trapping and dissolution. With active withdrawal (scenarios 1 – 5 in Fig. 5) the mobile scCO$_2$ in the formation decreases relatively fast after breakthrough of scCO$_2$ to the withdrawal well (Fig. 5b). Residually trapped scCO$_2$ increases as more mobile scCO$_2$ is trapped, but decreases due to dissolution (Fig. 5a). After breakthrough of scCO$_2$ to the withdrawal well, the scCO$_2$ plume does not further expand and additional
residual trapping stops. The residually trapped and mobile scCO₂ mass at the time of identifying the conditions of residual entrapment are shown (large circles) for scenarios 1, 2 and 5 in Fig. 5a and b, respectively.

![Fig. 5. (a) Residually trapped scCO₂ mass in the storage formation; (b) Mobile scCO₂. Large circles show the trapped mass (a) and mobile mass (b), respectively, at the time when conditions of residual trapping were identified in the test procedure.]

3.2. Effect of alternating CO₂ and water injections

Alternating the CO₂ injection with injections of brine leads a temporary decrease in the amount of mobile scCO₂ in the formation during the brine injection, but after injecting all the CO₂, the amount of mobile scCO₂ is larger compared to the base case (Fig. 6b). The amount of residually trapped CO₂ also increases slightly as a result of alternating CO₂ and brine injections and the increase is larger for a longer brine injection (tH₂O) (Fig. 6a). At the time when conditions of residual trapping were identified in the test (shown with large circles), both the trapped scCO₂ mass and mobile scCO₂ mass were larger for the scenarios with alternating CO₂ and brine injections compared to the base case.

![Fig. 6. (a) Residually trapped scCO₂ in the formation; (b) Mobile scCO₂ for scenarios with alternating CO₂ and brine injections compared to the base case. Large circles show the time when conditions of residual trapping were identified in the test procedure.]

4. Discussion

The interwell distance (D) influences several aspects of the proposed test to measure residual and dissolution trapping. A larger distance means that both the time of first arrival of scCO₂ to the withdrawal well and the time until a state of residual trapping has been reached are prolonged. Shorter distance, on the other hand, means that a large amount of the injected CO₂ will be withdrawn as mobile scCO₂ flowing out from the withdrawal well (Fig. 4b). The interwell distance together with permeability, also influences the shape of the scCO₂ plume. A large interwell distance can result in bypassing of part of the region between the wells due to buoyancy segregation of the scCO₂ plume as can be seen for D=100m in Fig. 3c.

This in turn also influences the amount of residually trapped scCO₂ in the formation when the mobile scCO₂ has mainly been removed. As can be seen in Fig. 5a, the amount of residually trapped scCO₂ at the time when a zone of residual trapping has been created is larger for D=50m than for D=30m. For D=100m the simulation was not run long enough to reach the state of residual trapping, however at the end of the simulation the amount of residually trapped scCO₂ had already decreased below that at residual state for the D=50 scenarios. This was likely a result of buoyancy effects on the scCO₂ plume, and indicates that to maximize residual trapping in the test, there is an optimal interwell distance which depends also on target formation permeability and thickness. In the case of the modelled Heletz formation the optimal distance to maximize residual trapping appears to be approximately 50m.

Higher permeability makes the vertical buoyancy-driven flow more important compared to the radial injection-driven flow of scCO₂ and therefore leads to more scCO₂ bypass of the lower part of the formation around the injection well. Lower permeability, on the other hand, requires both higher injection pressure and lower withdrawal pressure. In the case of the Heletz formation, k=10 x 10⁻¹⁵ m² was a too low to sustain the intended withdrawal rate, while for k = 50 and 100 x 10⁻¹⁵ m² the test was feasible.

A critical aspect is to be able to identify the conditions when most scCO₂ exist as residually trapped and most mobile scCO₂ has disappeared. This appeared to work well for scenarios 1, 2 and 5 (D = 30 or 50 m and k ≥ 50 x 10⁻¹⁵ m²) with clear changes in flux of scCO₂ to the withdrawal well (Fig. 4a). A further requirement is that the scCO₂ flux at formation depth can be measured.

Twice interrupting the CO₂ injection with an injection of formation brine slightly increased the amount of residual trapping. However, at the point in time when conditions of residual trapping could be identified, the amount of mobile scCO₂ remaining in the formation was also slightly higher. Therefore, alternating CO₂ and brine injections did not improve the capability of the test to measure residual trapping, but may slightly increase the total residual trapping as also suggested by other authors [4]. It should however be noted that a capillary pressure constitutive relation which includes hysteresis in the drying and wetting cycles is needed to fully evaluate the effects of the alternating CO₂ brine injections. Furthermore, heterogeneity, which was not considered in this study, will also affect the residual trapping.

5. Concluding remarks

An interwell field test to determine residual and dissolution trapping is being designed at Heletz, Israel. Numerical modelling was used to investigate the effects of different design and geological parameters on the outcome and feasibility of the proposed test methodology. Active withdrawal of fluids from one of the wells allows creation of a zone of residually trapped scCO₂ as well as measurements of component concentrations and tracers in extracted fluids. A critical aspect of the test is that a zone of residually trapped scCO₂ can be both created and identified. It was found that the interwell distance is critical for both these aspects and thereby for the success of the test. The optimal distance is site specific and depends on factors such as formation thickness, permeability and pumping rate employed in the test. For the Heletz site, interwell distances of 30 to 50 m were shown to be feasible for the proposed test. Too low
permeability can make the test unfeasible, but if the permeability is high enough that pumping rates can be sustained, it does not have a major impact on the test. Alternating CO₂ and brine injections slightly increased the amount of residual trapping but did not facilitate creation of a well-defined zone of trapping.

Acknowledgements

The research leading to these results has received funding from the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), project no 214-2008-1032, and from the European Community's 7th Framework Programme FP7/2007-2013, under grant agreement no 227286.

References