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Small-scale CO_2 injection into a deep geological formation at Heletz, Israel

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Abstract

This paper presents the experimental plans and designs as well as examples of predictive modeling of a pilot-scale CO_2 injection experiment at the Heletz site (Israel). The overall objective of the experiment is to find optimal ways to characterize CO_2 -relevant in-situ medium properties, including field-scale residual and dissolution trapping, to explore ways of characterizing heterogeneity through joint analysis of different types of data, and to detect leakage. The experiment will involve two wells, an injection well and a monitoring well. Prior to the actual CO_2 injection, hydraulic, thermal and tracer tests will be carried out for standard site characterization. The actual CO_2 injection experiments will include (i) a single well injection-withdrawal experiment, with the main objective to estimate in-situ residual trapping and (ii) a two-well injection-withdrawal test with injection of CO_2 in a dipole mode (injection of CO_2 in one well with simultaneous withdrawal of water in the monitoring well), with the objective to understand the CO_2 transport in heterogeneous geology as well as the associated dissolution and residual trapping. Tracers will be introduced in both experiments to further aid in detecting the development of the phase composition during CO_2 transport. Geophysical monitoring will also be implemented. By means of modeling, different experimental sequences and injection/withdrawal patterns have been analyzed, as have parameter uncertainties. The objectives have been to (i) evaluate key aspects of the experimental design, (ii) to identify key parameters affecting the fate of the CO_2 and (iii) to evaluate the relationships between measurable quantities and parameters of interest.

Keywords: CO2, injection experiment, modeling, instrumention

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1. Introduction

Predictions concerning the spreading, trapping and possible leakage of geologically stored CO_2 rely to great extent on model simulations. Before large-scale application of predicting storage performance, these models and modeling approaches need careful validation. This in turn requires well-controlled field experiments accompanied with comprehensive measurement and monitoring programs, that allow observing and monitoring the spreading of CO_2 in different phases. This work presents the experimental plans, principles of the key designs as well as preliminary results, of what is intended as a well-controlled, pilot-scale CO_2 injection experiment, to be carried out at the Heletz site (Israel), the main experimental site of EU FP7 R&D project MUSTANG (www.co2mustang.eu).

2. The injection experiment

The injection experiment will consist of injection of a small amount of supercritical CO_2 into a reservoir layer at about 1.5 km depth, associated with extensive monitoring and sampling. The overall objective of the experiment is to find optimal experimental ways to characterize CO_2 -relevant in-situ medium properties, including field-scale values for the two key trapping mechanisms, residual and dissolution trapping, to explore ways of characterizing heterogeneity effects through joint analysis of different types of data, and to detect leakage. A secondary objective is to form consistent and comprehensive data sets for model validation.

The experiment will involve two wells, one injection well and one monitoring well. These wells will be instrument§§ed for detailed monitoring and sampling. Two CO_2 injection experiments with small amounts of CO_2 are to be carried out. The first one is a single well injection-withdrawal (push-pull) experiment, with the main objective to evaluate the in-situ residual trapping of CO_2. The second one is a dipole experiment, where CO_2 will be injected in the injection well while simultaneously pumping in the monitoring well, thereby creating a dipole and directing the flow of CO_2 towards the monitoring well. Prior to the injection experiment, hydraulic and tracer tests will be carried out to characterize layer properties. Tracers will be introduced in both experiments and into both fluids (water and CO_2) to aid in detecting the development of the phase composition during the CO_2 transport. In addition, geophysical monitoring will be carried out.

2.1 The Site

The Heletz site is a depleted oil reservoir filled with brine at its edges. The experiment will be carried out in the northeastern brine part of the formation, in the vicinity of well Heletz 18. The geology of the site is relatively well characterized through the large number of boreholes drilled for oil exploration purposes. The three sandstone layers (so-called Heletz sands) which are overlain by a relatively thick shale caprock will be the target layers for the injection. Example cross-section in the vicinity of the planned injection experiment is shown in Fig.1. In the section, the target layers appear as continuous units marked by yellow color within the depth range of 1450-1500m.

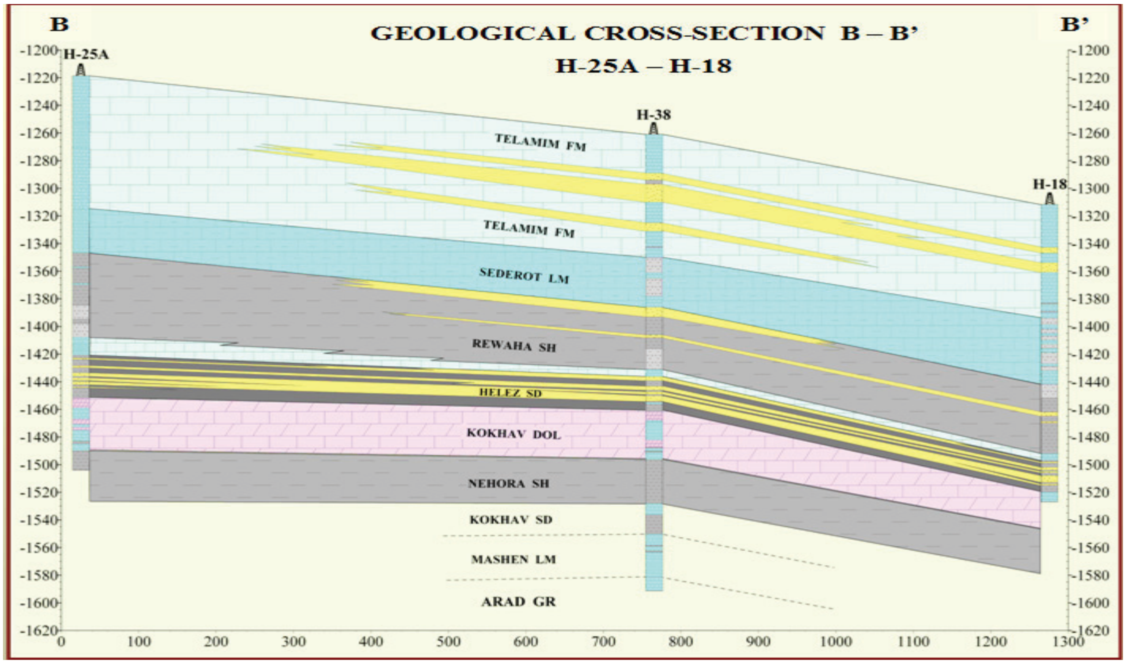

Fig. 1. Example cross-section of the Heletz site.

2.2 Pre-injection experiments

Prior to the actual CO_2 injection experiments, preparatory testing will take place to characterize the hydraulic properties of the formation. First, in the injection well, hydraulic, thermal and tracer tests will be carried out. Thermal logging will be used for defining the temperature profile, hydraulic pumping tests for determining the overall hydraulic properties, and flowing fluid electric conductivity logging (FEC) [1][2] to determine the detailed conductivity structure inside the layers. Push-and-pull single-well tracer tests will be used for determining fluid-rock interface densities.

After the drilling of the monitoring well, hydraulic tests as well as standard tracer tests will be carried out in the two-well system, to determine the water flow velocities, flow path connectivity and effective porosity between the two wells, as well as to get a preliminary understanding of the inter-well flow path heterogeneity and to aid in finalizing the design of the CO_2 injection test. The approach of the tracer tests is described in more detail in [3].

2.3 Single-well injection-withdrawal experiment

The single well injection-withdrawal experiment will follow the design by Zhang et al [4] planned for the Otway site in Australia. As described in more detail in [4], the objective of this experimental design is to get an estimate of the in-situ residual trapping of CO_2. An example test sequence is given in Figure 2a. The test sequence consists of three main sections: (i) sequence of reference testing where the conditions (temperature and pressure) in response to heating and water injection/withdrawal are recorded in natural conditions with no free-phase CO_2 in the formation, (ii) sequence to create the zone of residual CO_2 which is achieved by first injecting a pulse of supercritical CO_2, followed by the injection of CO_2-saturated water which will push the mobile CO_2 away from the well (while avoiding any dissolution into the injected aqueous phase, therefore the injection of CO_2 saturated water) thus creating a zone of residual CO_2 near the well and finally, (iii) sequence of tests similar to phase (i) to observe whether the measurable quantities (pressure and temperature) can provide information about the residual saturation of CO_2 in the formation. In the case of pre-experiment modeling of the push-pull experiment [8], a key issue has been to find the best pumping scheme to allow determining the in-situ residual $scCO_2$ (sc referring to supercritical) saturation as well as dissolution from the available measurements. Example simulation result with medium properties from Heletz (simulated with TOUGH2/ECO2N code [5], [6], assuming Heletz-18 as the injection well) is shown in Fig. 2b. Looking at how such pressure responses – and similarly also temperature responses - vary depending on the in-situ residual saturation of CO_2, allows estimating the residual saturation. So far our preliminary results with the properties from Heletz indicate that pressure response may show more of a difference than temperature and may therefore aid more in the estimation process. With the medium properties from well Heletz-18 and the test sequence in Fig. 2a, the preliminary simulations indicated that, for example, a residual CO_2 saturation of 0.09 would cause an observed pressure difference of 1.5 MPa in comparison to the reference situation, while a residual saturation of 0.19 would cause a difference of 6.0 MPa. Differences in temperature response to heating at reference and residual CO_2 saturation conditions was also noticed, being lest than 1˚C for both of above residual saturation cases. The simulations have so far not taken into account capillary hysteresis, which is likely to influence a system like this where alternating non-wetting and wetting phase invasion is taking place.

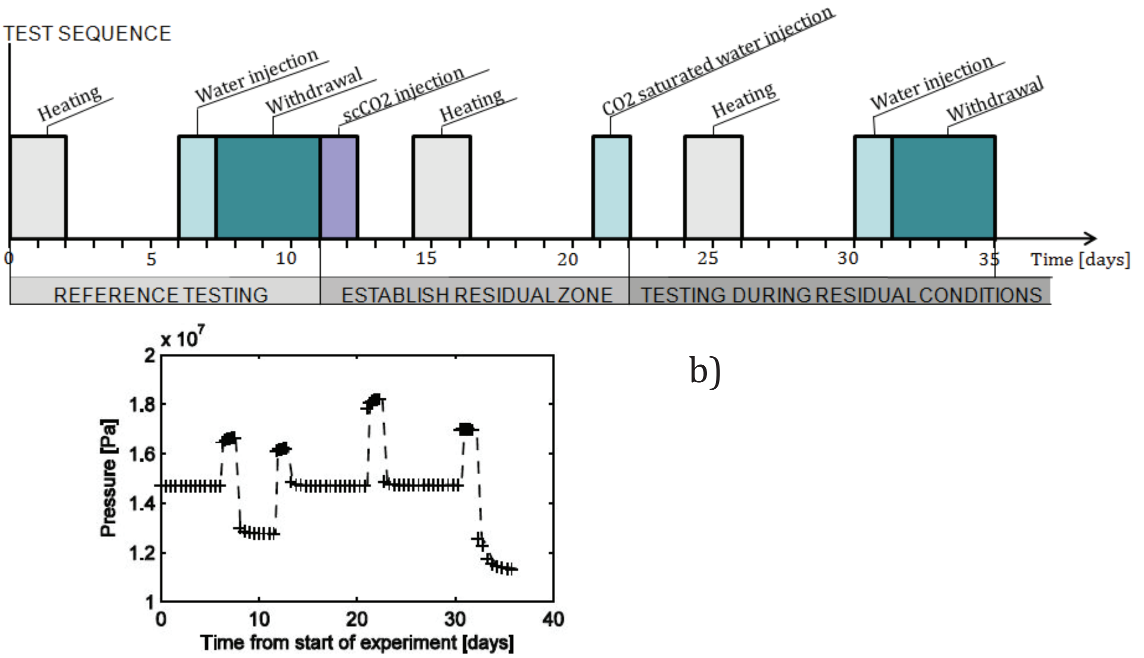

Fig. 2. a) An example test sequence for the single-well injection withdrawal test adopted from [4] and b) and an example simulated pressure response with Heletz properties

2.4 Dipole CO_2 injection experiment

After the push-pull experiment, a two-well CO_2 injection-withdrwal test will be carried out, where a small amount of CO_2 (under 1000 ton) will be injected through the injection well and its arrival be monitored in the monitoring well, by means of pressure and temperature monitoring as well as fluid sampling. Geophysical monitoring from the boreholes will be applied as well. During the injection, water will simultaneously be pumped from the monitoring well in order to create a dipole and to guide the CO_2 into the monitoring well, partly to speed up the transport, partly to assure that a large part of the CO_2 will be recovered. Some of the main objectives of this experiment are to understand the transport and trapping of CO_2 during its transport in heterogeneous media and to develop approches for interpreting CO_2 relevant medium properties from such experiments, by joint analysis of different types of data. While combined interpretation of pre-experiment hydraulic and tracer data together with data on CO_2 breakthrough will give information on CO_2 transport and its interpretation in heterogeneous media, the use of partitioning [3] and potentially also so-called so-called kinetic interface-sensitive (KIS) tracers [7] will give information about the development of the interface between supercritical CO_2 and brine, which is a key parameter for the dissolution of CO_2 during the transport. The principle of these tracers is presented in more detail in [7]. Design issues that have been addressed by predicitive modeling [9] include i) effect of dipole distance, ii) optimal injection/withdrawal sequence including the possible benefits of alternating CO_2 injection with water injection and iii) role of formation heterogeneity, both due to uncertainties in the mean properties of the reservoir layers as well as due to the effect of the stochastic type of heterogeneity inside the layers. The effect of heterogeneity is - as can be expected – important, causing uncertainty in the estimation of the arrival time. It appears that, with the medium properties available here, even a relatively small contrast in layer permeabilities made the most conductive layer the dominant one. This appears to be due to the self-enhancing effect of increased gas (free phase CO_2) permeability in the layer with higher permeability where the CO_2 first starts to spread.

Fig. 3. shows examples of simulated $scCO_2$ distributions with active abstraction of fluids from the updip monitoring well for different dipole distances as compared to passive monitoring only (no pumping) in the monitoring well (Fig 3a.), along with a simulated distribution of dissolved, supercritical and pumped-out CO_2 during the experiment (Fig. 3b.). As can be seen in Fig. 3, the larger dipole distance (100 m) stretches the $scCO_2$ plume more, and the CO_2 arrives later to the abstraction well. With the shorter distance – and same duration of pumping – a large part of CO_2 will be pumped out of the system, which maybe is not optimal in terms of retrieving information of in-situ behavior of CO_2.

The simulated base-case scenario for injection and abstraction of fluids was injection of 1000 tons of supercritical CO2 at a rate of 5 tons/hour followed by injection of water with tracers for one day. During injection there was simultaneous abstraction of fluids in the monitoring well at the same rate (except the "passive monitoring" simulation case) This water injection which functions as a hydraulic and tracer test when CO2 is present in the formation produces a dip in the supercritical CO2 distribution, which can be seen in Fig. 3a (dipole cases). Abstraction was continued after the end of the injections to continue drawing the fluids towards the monitoring well, however, similar to in the single-well test sequence (Fig. 2), breaks in the simulated fluid abstraction were made for thermal measurements and cross-hole geophysics. Further simulations of different injection-abstraction scenarios showed that additional water injection significantly increased dissolution leading to removal of a large part of the mobile $scCO_2$. Continuous abstraction (no abstraction breaks during thermal and geophysics measurements) significantly increased the CO_2 migration up-dip towards the abstraction well, while dissolution was not markedly increased.

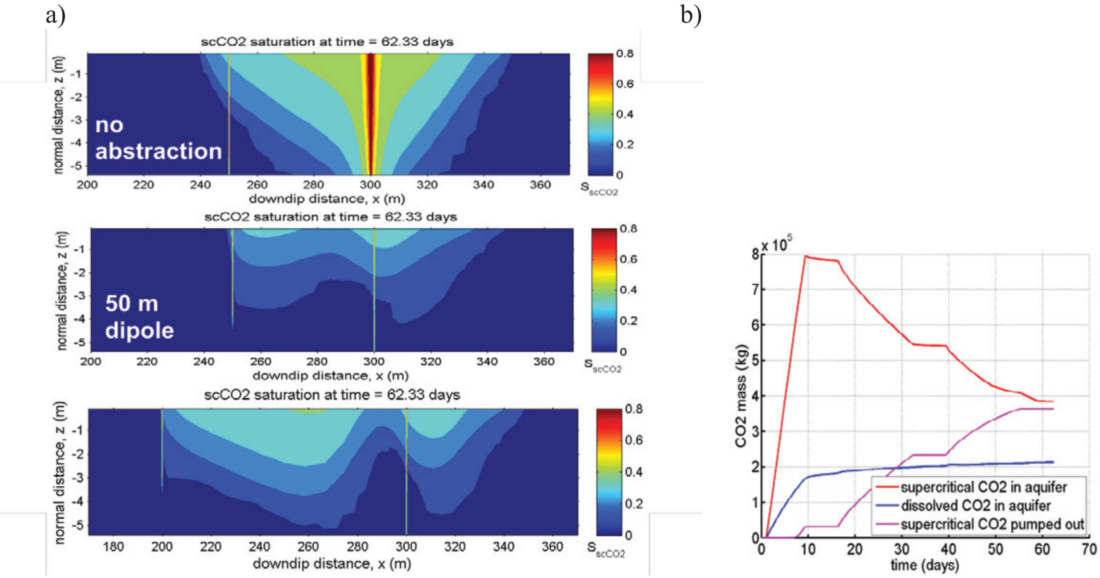

Fig. 3. a) A simulated $scCO_2$ distribution for different dipole configurations; no abstraction, 50 m dipole and 100m dipole (listed from top to bottom, injection well to the right and monitoring well on the left) and b) development of different CO2 mass fractions during the experiment for the short dipole distance.

Fig. 4 shows how permeability in the different layers affects the migration of the supercritical CO2 depending on the permeability contrast between the layers. The simulation result shown Fig. 4a is based on "best estimates" of the permeability in the different layers following interpretation of well logs together a permeability-porosity relationship from measurements on rock cores. Because considerable uncertainty in the best estimates of permeability will exist until hydraulic testing of individual layers has been performed, a study of the effect of different permeability contrasts was also performed. Results are exemplified in Fig. 4b showing the simulated CO2 migration for no contrast (same layer properties), and in Fig. 4c showing the maximum migration distance of the supercritical CO2 front for different permeability contrasts between layers. The target formation has three conductive sub-layers named A, W, and K. In the "best estimate" (BE) model there is a permeability contrast of a factor 2 between the least permeable A-layer and the K-layer and a factor-5 contrast between the A- and W-layers. Other models include no permeability contrast (same layer properties: SLP), and larger contrast; factor 4 A-K and 10 A-W: (K4W10 model) and factor 8 A-K and 20 A-W: (K8W20 model). The results, as illustrated in Fig. 4, showed that the permeability contrast simulated in the best estimate model was enough to produce strong domination of the most permeable (W) layer and a preferential flow of CO2 in this layer. For the case of no contrast between the layers (SLP model) the results were markedly different as supercritical CO2 was much more evenly distributed between the layers and the front did not reach the abstraction well. The results also showed (Fig. 4c) that further increasing the permeability contrast does not have any large effect on the supercritical CO2 migration. It can be concluded that a relatively small permeability contrast between the conductive layers in the target formation can produce a strong preferential flow in the most conductive layer. Another finding was that the permeability contrast between layers didn't appear to affect the amount CO2 dissolution.

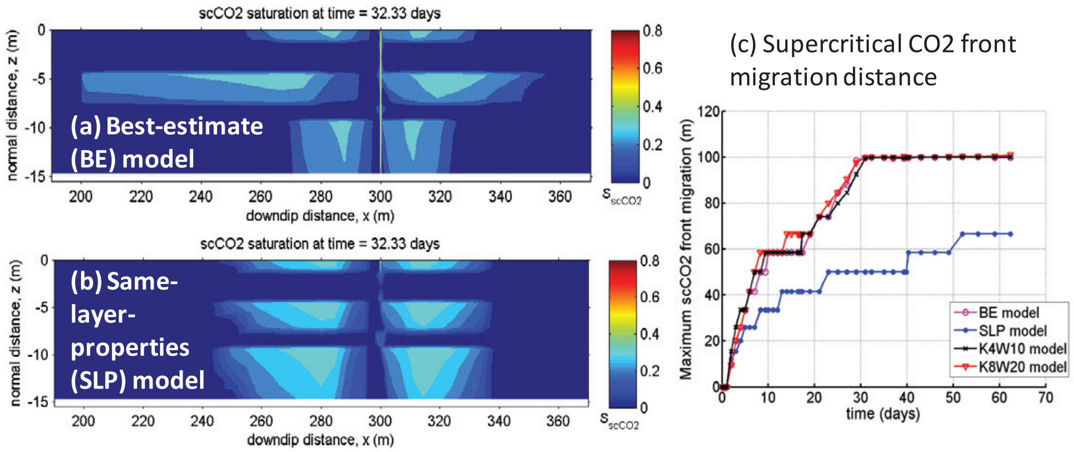

Fig. 4. Simulated supercritical CO2 migration in different layers of the target formation for different permeability contrasts between these layers. (a) Best-estimate permeability model, (b) Same-layer-properties model, (c) comparison of the front migration distance for different permeability models. Injection well is at x=300m and abstraction well at x=200m.

2.5 Instrumentation and laboratory testing

The experimental program requires sophisticated instrumentation in both wells, to enable e.g. a simultaneous pumping, sampling and monitoring in both wells and in multiple layers. The injection well will be instrumented to allow injection of water and CO_2, withdrawal of water, monitoring pressure and temperature, fluid sampling at depth, continuous temperature and pressure measurements by means of an optical fibre, as well as seismic monitoring. The monitoring well will be instrumented to allow pressure and temperature measurement and fluid sampling at different vertical horizons (above the seal, inside the seal and at different intervals in the target layer). It will be possible to pump from the monitoring well during the injection operations, in order to create a directed flow field.

In support of the field experiments, laboratory testing will be carried out as well, to determine rock properties and analyze the fluid samples. On-site fluid sample analysis facilities are presently under construction.

3. Concluding remarks and outlook

MUSTANG project started 2009. Concerning the Heletz experiment, the first two years have been intensive planning of the test and the equipment needed. Field activities started in late 2010 and construction of the injection/monitoring equipment in 2011. The first well (the injection well) is planned to be drilled by December 2011, after which the standard well logging will be carried out and the well instrumented for the injection, monitoring and sampling. After this, standard well tests (hydraulic and tracer tests) in single-well mode will be carried out as well as interpreted during spring 2012. The drilling of the monitoring well is planned to commence immediately after the drilling of the first well, followed by standard logging, well preparation and instrumentation, and finally standard hydraulic and tracer tests in the two-well system. After interpretation of the standard hydraulic and tracer tests, the push-pull injection of CO_2 is planned to take place during summer 2012, followed by the two-well CO_2 injection test in the dipole mode during autumn 2012.

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