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Field experiment on CO₂ back-production at the Ketzin pilot site

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Abstract

At the Ketzin pilot site for CO₂ storage, 67 kt of CO₂ were injected between 2008 and 2013 into a saline aquifer. In October 2014, part of the formerly injected CO₂ was retrieved from the reservoir. 240 t of CO₂ and 55 m³ of brine were back-produced and an interdisciplinary monitoring accompanied the field experiment. It indicates that a safe CO₂ back-production is feasible and can be performed at both, stable reservoir and wellbore conditions.

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1. Introduction

The Ketzin project was initiated by the GFZ German Research Centre for Geosciences in 2004 as the first onshore project in Europe which is dedicated to research and development for a better understanding of geological CO₂ storage [1-5]. The injection phase of the Ketzin pilot site 25 km west of Berlin started in June 2008 and ended in August 2013 and provided valuable experience in operating a CO₂ storage site [6]. Over the period of 62 months, a total amount of 67 kt of CO₂ was successfully injected into a saline aquifer (Upper Triassic sandstone) at a depth of 630 - 650 m. The CO₂ used was mainly of food grade quality (purity > 99.9 %). In addition, 1.5 kt of CO₂ from the pilot capture facility “Schwarze Pumpe” (lignite power plant CO₂ with purity > 99.7 %) was used in 2011. At the

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end of the injection period, 32 t N₂ and 613 t CO₂ were co-injected during a four-week field test in July and August 2013 [7].

From 15th to 27th October 2014, a part of the formerly injected CO₂ was retrieved from the reservoir via one well and vented to the atmosphere (“back-production experiment”). A total amount of 240 tons of CO₂ and 55 m³ of brine were safely back-produced from the CO₂ storage reservoir. This field experiment addressed the following three main questions:

- (i) How do the reservoir and the wellbore behave during back-production of CO₂?
- (ii) What is the composition of the retrieved gas?
- (iii) How is atmospheric gas composition and distribution?

In this paper, we give a comprehensive overview on the technical concept for the test operation and outline the monitoring results for (i) and (ii). The results of the atmospheric monitoring with ground-based tools for aspect (iii) are described in Schütze et al. (2015) [8].

2. Technical method and test regime

The test equipment was selected to meet process safety considerations and thermodynamic behaviour of the CO₂. A photographic enhanced piping and instrumentation diagram is given in Figure 1. A safety valve was attached to the wellhead of Ktzi 201 which was used as production well as a general safety precaution. The retrieved CO₂ was heated up to about 50 °C with an indirect heater to prevent dry ice formation due to Joule-Thomson effect when releasing and expanding the CO₂ to atmospheric pressure at the vent-off stack. The flow rate was controlled by a choke manifold and measured by a coriolis type flow meter. The produced formation water was separated and degassed in a gauge tank. The CO₂ was released into the atmosphere with a silenced vent-off stack about 6 m above ground level. All testing equipment was hired from a service company of the oil and gas industry.

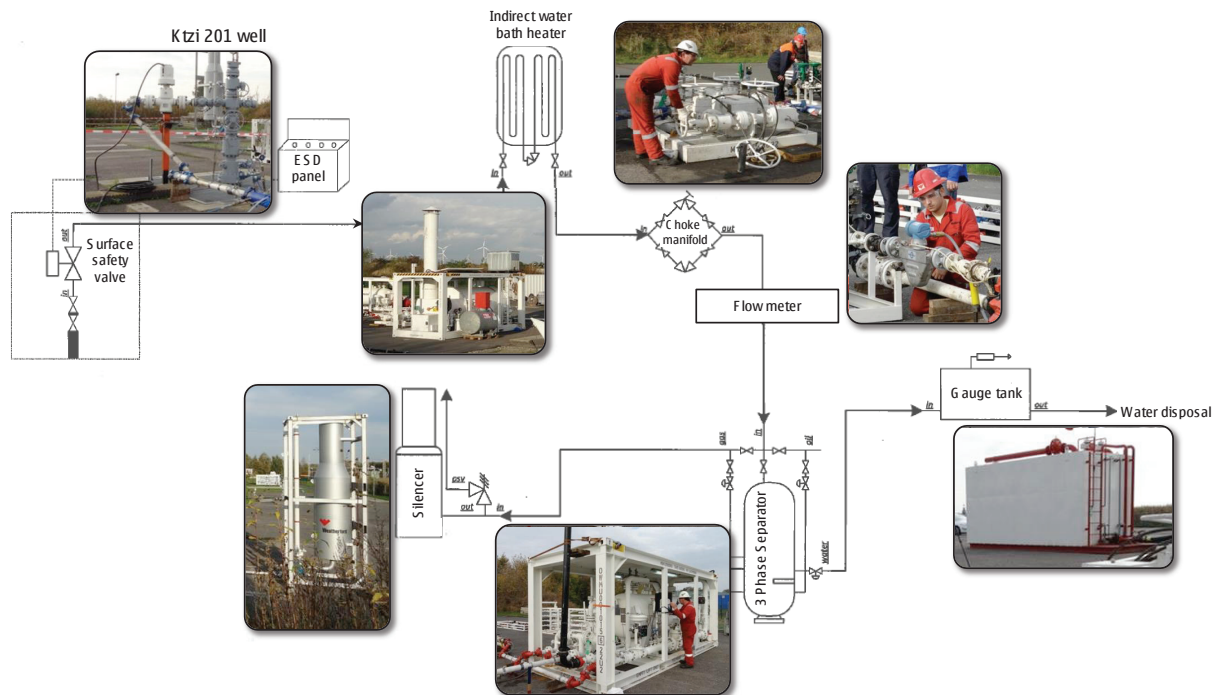


Fig. 1. Technical components for the back-production test (photographs by GFZ).

The test was conducted in five main phases for a total duration of 13 days (Figure 2):

- 15th October: 2014: The equipment was commissioned and different flow rates up to ~3,600 kg/h tested.
- 15th to 20th October 2014: Continuous operation with mean flow rate of ~800 kg/h was performed.
- 20th to 22nd October 2014: The flow rate was increased to ~1,600 kg/h on 20th October and continuous operation continued until October 22nd.
- 22nd to 27th October 2014: Operation switched to an alternating regime with a mean flow rate of 800 kg/h during day shift and switch off during night shift.
- 27th October 2014: The flow rate was ramped down in 100 kg/h steps from 800 to 200 kg/h and the field experiment terminated.

3. Monitoring results

3.1. Pressure and temperature conditions

During the test, pressure and temperature conditions were continuously monitored at 550 m depth inside the production tubing of well Ktzi 201 and at the wellhead (Figure 2). All operational data which was recorded has been published by Möller et al. (2015) [9].

According to Figure 2 the downhole temperature measurements show very stable conditions over the entire course of the test. Neither the start-up phase nor stable operation at different rates and the on/off conditions affected the temperature significantly. Nevertheless, there are slight bumps in the start-up phase followed by a smooth transition to stationary conditions. Interestingly, during the alternating regime the downhole temperature rises by approximately 0.5 °C during shut-in phases and releases once the back-production commences.

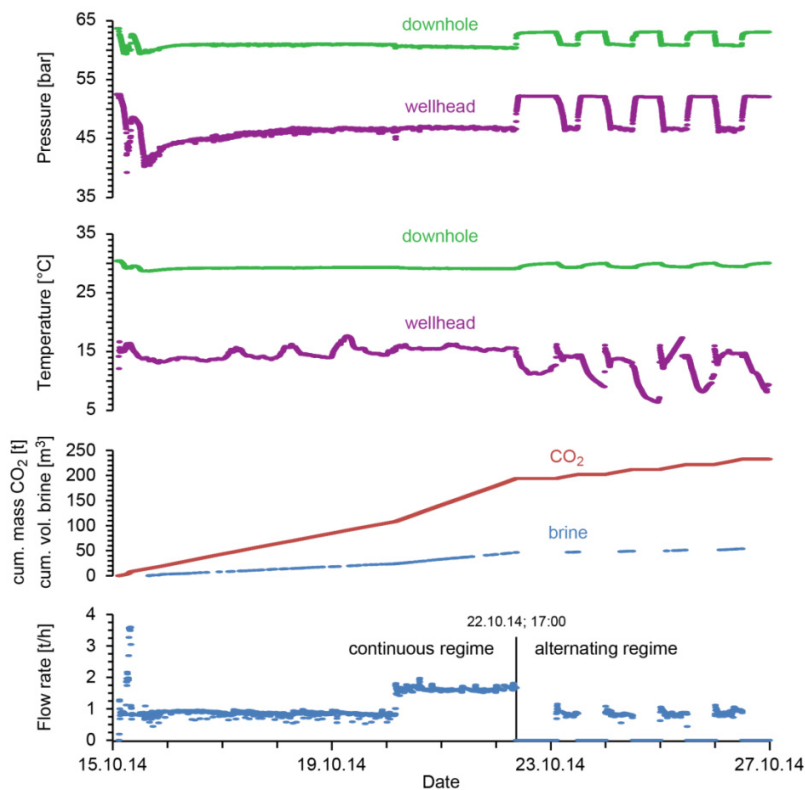


Fig. 2. Bottom: Flow rates during the CO₂ back-production test and cumulative mass of retrieved CO₂ (red) and brine (blue); Top: Results of pressure and temperature monitoring.

The wellhead temperature shows stronger variations over time, especially pronounced during the start/stop regime from October 22th onwards. These variations reflect the strong influence of solar radiation over the course of the day. Several peaks in the temperature curve occur around noon and notable diurnal variations last until late afternoon on October 20th. With the doubling of the production rate this very day, temperature is now dominated by the wellbore fluid so that the curve is running near-flat until the beginning of the alternating regime on October 22th. During this phase, temperature drops down significantly during the nights since it is mostly influenced by the ambient temperature and absence of sunlight.

With start of back-production, the downhole pressure decreases from pre back-production conditions of ~ 65 bar and stabilizes already after one day at ~61 bar apart from the later alternating start/stop regime. During shut-in phases, downhole pressure almost immediately increases to about 0.5 bar below the initial pressure within a matter of hours and returns to steady-state values of ~61 bar once the back-production commences. The same holds true for the wellhead pressure although the settling time until stationary conditions of ~46.5 bar are reached is several days compared to hours for the downhole pressure. Interestingly, the pressure response during the alternating regime is as fast as the downhole pressure reaction to a similar 0.5 bar stand-off below the original pressure before the test. From the wellhead and downhole pressure and temperature data, the corresponding CO₂ densities have been calculated. Pressure and temperature data during active back-production correspond to CO₂ densities of about 180 kg/m³ downhole and about 130 kg/m³ at the wellhead and clearly indicate single phase gas flow.

3.2. Geoelectrical monitoring

The field test was accompanied by geoelectrical crosshole measurements based on the permanent downhole electrode array in the wells Ktzi 200, Ktzi 201 and Ktzi 202 [10]. During the back-production period, the frequency of the originally weekly conducted crosshole measurements was intensified towards daily surveys. Only on October 18th/19th 2014, a lack of ERT data occurred due to technical reasons.

A direct indication of near-wellbore effects due to the back-production process is given by the raw data of the so-called contact resistance measurements. These resistance values are recorded as pre-survey check before the regular crosshole measurement starts and provide information about the coupling situation of each individual electrode of the array to its surrounding (Figure 3).

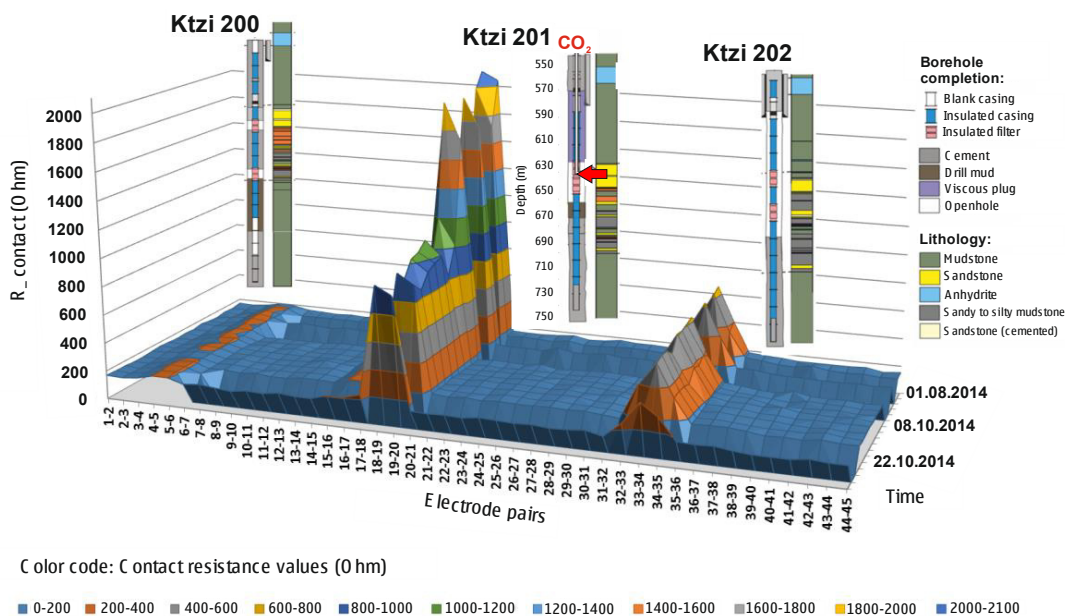


Fig. 3. Color coded plot of contact resistance values of the permanent downhole electrode array in three Ketzin wells: Ktzi 200 (electrodes #1-#15), Ktzi 201 (electrodes #16-#30), and Ktzi 202 (#31-#45). During the back-production of CO₂ and brine a significant decrease of contact resistances measured at the electrodes in the upper region of the filter screen at Ktzi 201 occurs (electrodes #17-#20).

In case of non-changing coupling conditions, the contact resistances show equal values with only minor noise-induced variations between the individual crosshole time steps. Such a steady-state behavior can be observed in the well Ktzi 200 due to its sufficiently filled annular space. For the well Ktzi 202, a similar stable contact resistance behavior occurred since the partial abandonment in October 2013 [11], where the lower part of the well changed from open-hole stage to a sufficiently filled annulus along the electrode array zone. In the well Ktzi 201, varying contact resistances may occur according to the changing fluid or gas conditions in the near-wellbore area due to the existing open annular space above and below the filter region. The specific contact resistance behavior of the 15 electrodes per each well is shown in Figure 4. Here one can clearly see that in the months of August and September 2014 (post-injection phase) stable contact resistances of about 2000 Ω exist in the upper region of the filter screen at the well Ktzi 201 (electrodes #17-#20). During the start of the back-production process, these resistances were reduced towards values of about 800-1000 Ω due to brine intrusion into the annular space.

Given the fact that for the taken daily geoelectric 3D survey only one resistance check could be recorded by technical constraints of the existing ERT readout unit, the time resolution of the contact resistance values during the back-production process and its varying rates seems to be very limited. Regardless, Figure 4 demonstrates that the variation at the corresponding electrodes #18-#19 and #19-#20 due to their contact with ascending saline formation fluid is significant enough to provide a clearly noticeable trend. Coincidentally, the daily resistance check was conducted mostly at times of higher production rates which are correlated with a direct pressure drop. Therefore, the observed electrodes approached the level of 800 Ω. At the end of the back-production period, the contact resistance values tend to relax back to their former high level of about 2000 Ω.

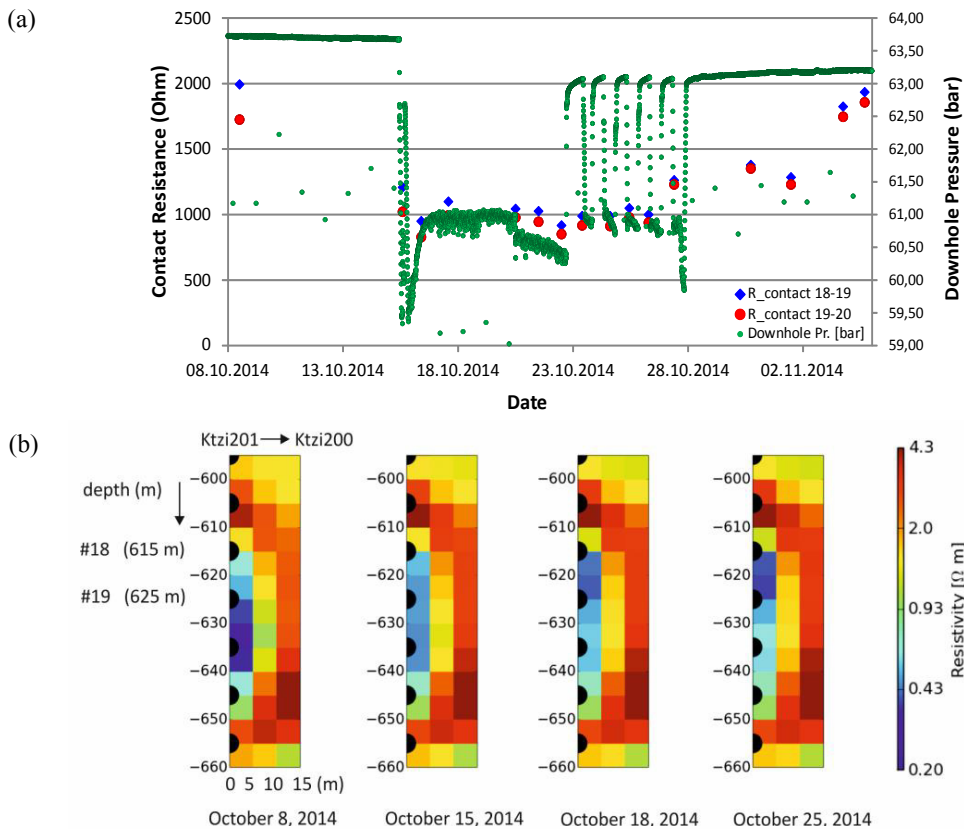


Fig. 4. (a) Ktzi 201 well: Variations of contact resistance values in the upper filter region (electrodes #18-#19, #19-#20) correlate with the pressure variations (downhole pressure, measured at 550 m). (b) Ployout of 2D ERT tomography sequence, which indicates the effect of ascending formation water in the near-wellbore area of Ktzi 201, visible by the bluish colors which stands for a more conductive influence.

According to the predicted back-production scenario by reservoir simulations, the velocity of the released CO₂ was high enough to produce also a certain amount of formation water. This saline water is dispersed and entrained by the stream of CO₂ up to the wellhead, forming a water cone along the filter region which is detectable via the contact resistance values.

The inverted geoelectrical data of Figure 4b confirm this behavior in the near-wellbore area, i.e. that saline formation water is ascending from the original brine level at about 639 m depth (October 8th 2014) and back-produced together with the flowing CO₂, as seen in the time steps from October 15th, 18th and 25th. The tomographic sequence shows a significant lowering from higher resistive values towards a more conductive environment for the electrodes #18 and #19 in the upper filter region of the Ktzi 201 well. This underlines the predicted behavior of water coning and simultaneous extraction of brine and CO₂ from the sandstone.

3.3. Gas monitoring

The produced gas was sampled every 20 minutes behind the gas/water separator and analyzed using a gas chromatograph (SRI Instruments, 8610C with a TCD detector). Missing data either represent operational or analytical breaks.

The results show that the retrieved gas consisted of > 97 Vol-% CO₂ plus N₂. Both gases were detected instantaneously from the beginning of the experiment (Figure 5). The CO₂ concentration continuously increased from 97.2 to 98.6 Vol-% until the operation was changed to the alternating regime. The modification to a discontinuous back-production resulted in slightly lower CO₂ concentrations at the beginning of the daily restarts and a subsequent increase during the day. During the last three days of the test the CO₂ concentration reached a constant level of about 98.8 Vol-%. The N₂ concentration decreased from about 2.8 to 1.2 Vol-% during the course of the experiment. Additionally, minor amounts of CO (< 50 ppm) as well as Kr and SF₆ (< 10 ppm, both were used in previous tracer tests, e.g. in 2013) were detected. The doubling of the production rate on October 20th 2014 did not lead to a significant change in the concentration of the major components.

The gas composition of local natural formation fluids showed that CH₄ (0.17 mg/l fluid), CO₂ (0.08 mg/l), H₂ (0.14 mg/l) and N₂ (17.9 mg/l) were the main components before the injection of CO₂ started [12]. The higher N₂ concentration measured during the back-production test therefore most probably results from the N₂-CO₂ co-injection test conducted in summer 2013 [7]. As in total only 240 t of gas were retrieved during the back-production in 2014 merely a small area around the well Ktzi 201 was tapped where residual N₂ was still available.

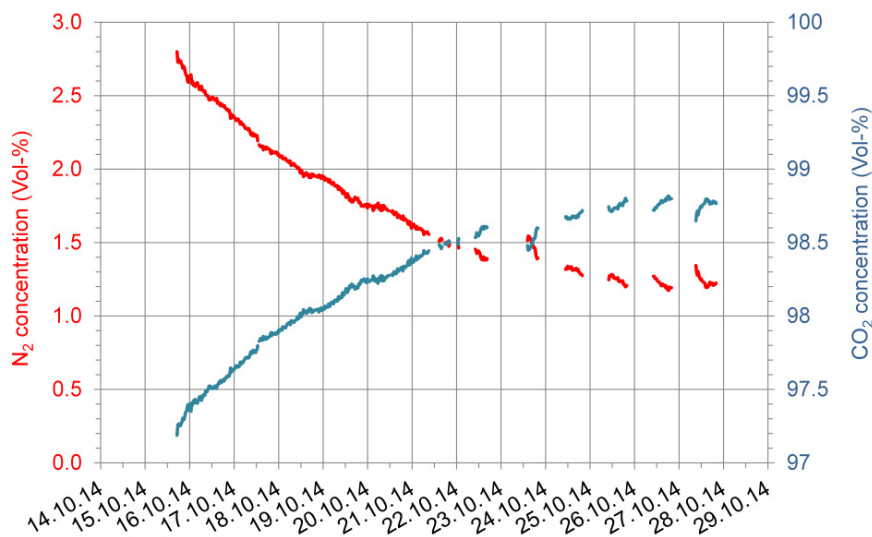


Fig 5. Results of the gas monitoring during the back-production test: CO₂ (blue curve, values on secondary y-axis) and N₂ (red curve, values on primary y-axis) are the main components of retrieved gas.

4. Numerical simulations and results

The numerical simulations of CO₂ back-production at Ketzin were undertaken in two steps. First, a predictive simulation run was carried out to elaborate estimates on the potential well flow rates of gaseous CO₂ and formation brine during the scheduled field-test. The simulation results were then considered in the planning and design of the field test, i.e., for refinement of monitoring layout and verification of cost estimations on formation brine intermediate storage and disposal. Thereafter, we used the valve-determined flow rates applied during the field test as limiting boundary condition in a second simulation run, considering the effective time schedule of the test and the maximum allowed flow rates adjusted at the release valve.

Both simulation runs were based on the history-matched reservoir model [13], [14]. This calibrated reservoir model is applicable to establish reliable short- to mid-term predictions of reservoir pressure development by numerical simulations [15]. We employed the Schlumberger ECLIPSE 100 black-oil simulator [16], using a minimum downhole pressure of 59 bar at 620 m depth and atmospheric pressure conditions at the wellhead as boundary conditions for the well model in both simulation runs. An effective maximum well flow rate limit was set in the second simulation run, determined by the valve settings made during the field test to consider all manual flow rate reductions, while the first run used the scheduled maximum allowed flow rates. Since the initially scheduled and effective flow rates realized in the field experiment differ in their magnitudes and time, only the results of the second simulation run are discussed in the following.

Figure 6 shows the comparison between the simulated and observed cumulative produced CO₂ and formation brine. Simulated CO₂ back-production amounts to about 205 metric tons at the end of the field test, while the observed CO₂ back-production is about 240 metric tons (underestimation by about 14 %). Total co-production of brine is overestimated by about 39 % in the numerical simulations (about 91 sm³) compared with the observed co-production (about 55 sm³). These deviations are expected to result from the wellbore model implementation, i.e., the lack of vertical flow profiles for the Ktzi 201 well, the relatively coarse lateral grid size (5 m x 5 m) in the well block elements and potential differences in the near-well (<5 m radius) CO₂ saturation. Detailed investigations are scheduled to assess the simulated gaseous CO₂ saturation in the near-well area by comparing simulation results with data from ERT and pulsed-neutron gamma (PNG) logging campaigns.

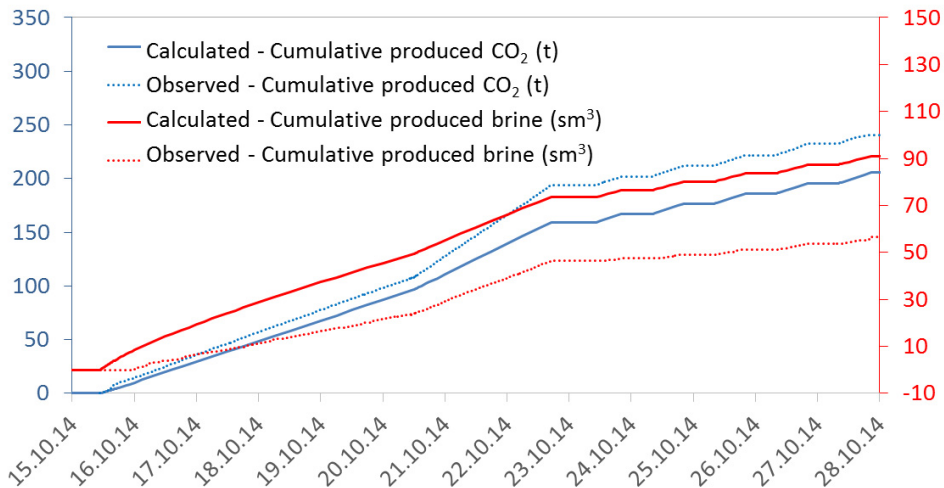


Fig. 6. Comparison between the observed (dotted lines) and simulated (solid lines) back-produced gaseous CO₂ (blue lines, values on primary y-axis) and co-produced formation brine (red lines, values on secondary y-axis). Total CO₂ back-production is underestimated by about 14 %, while co-production of brine is overestimated by about 39 % in the numerical simulations based on the history-matched reservoir model of the Ketzin pilot site.

5. Conclusion and outlook

The field experiment conducted at the Ketzin pilot site in October 2014 indicates that a safe back-production of CO₂ is generally feasible and can be performed at both, stable reservoir and wellbore conditions. Over a two-week period a total amount of 240 t of CO₂ and 55 m³ of brine were safely back-produced from the reservoir.

ERT monitoring shows that the geoelectrical array at the production well was capable of tracking the back-production process, e.g. the back-flow of brine into the parts formerly filled with CO₂. Preliminary results also show that the back-produced CO₂ at Ketzin has a purity >97 %. Secondary component in the CO₂ stream is N₂ with <3 % probably results from former field tests. The results will help to verify geochemical laboratory experiments which are typically performed in simplified synthetic systems. Numerical simulations were carried out in advance of the field test to support its design. Considering its effective time schedule and the maximum allowed flow rates, the total amount of back-produced CO₂ was underestimated by about 14 % in the numerical simulations.

The results gained at the Ketzin site refer to the pilot scale. Upscaling of the results to industrial scale is possible but should be first tested and validated at demonstration projects.

The overall aim of the Ketzin project is to close the life-time cycle of a CO₂ storage site at pilot scale. Further activities within the post-closure phase are e.g. the successive abandonment of all wells and the continuation of monitoring including the third 3D seismic repeat in fall 2015. The next field experiment will focus on a small-scale brine injection into the CO₂ reservoir in order to study e.g. the residual gas saturation and the potential as a means for wellbore leakage mitigation.

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