Govindan, R., Si, G., Korre, A., Durucan, S., Wiese, B., Schmidt-Hattenberger, C., Liebscher, A. (2017): The Assessment of CO2 Backproduction as a Technique for Potential Leakage Remediation at the Ketzin Pilot Site in Germany. - *Energy Procedia*, *114*, pp. 4154—4163.

DOI: http://doi.org/10.1016/j.egypro.2017.03.1556

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 114 (2017) 4154 – 4163

Energy Procedia

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

The assessment of CO_2 backproduction as a technique for potential leakage remediation at the Ketzin pilot site in Germany

Rajesh Govindan[a,*], Guangyao Si[a], Anna Korre[a], Sevket Durucan[a], Bernd Wiese[b], Cornelia Schmidt-Hattenberger[b], Axel Liebscher[b]

[a]*Department of Earth Science and Engineering, Royal School of Mines, Imperial College London, London SW7 2BP, United Kingdom*
[b]*GFZ German Research Centre for Geosciences, Helmholtz Centre, Telegrafenberg, 14473 Potsdam, Germany*

Abstract

As part of the license application, CO_2 storage projects must develop a corrective measures plan, which describes the steps that can be taken when the plume in the subsurface behaves in an unpredicted and undesired manner. One possible technique in the toolbox of corrective measures is CO_2 backproduction, which has the potential for both pressure management and plume steering in the reservoir. The feasibility of this technique has recently been tested during a field experiment at the Ketzin pilot site in Germany. In this paper, the authors describe an assessment of backproduction using coupled flow and geomechanical modelling. In line with the field observations, the simulation results obtained also suggest that it is a stable and promising remediation technique.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: Ketzin pilot site; saline aquifers; CO_2 backproduction; leakage remediation; Markov chain geostatistics

1. Introduction

Located at about 25 km West of Berlin, in the Federal State of Brandenburg, in North Germany, the Ketzin pilot site for CO_2 injection helped gain a comprehensive knowledge on the storage process through the application of a

* Corresponding author. Tel.: +44-20-7594-7370.
E-mail address: r.govindan07@imperial.ac.uk

Peer-review under responsibility of the organizing committee of GHGT-13.
doi:10.1016/j.egypro.2017.03.1556

unique and multidisciplinary monitoring program during the period June 2008 to August 2013 [1]. By the end of this period, a cumulative mass of slightly over 67 kt of CO_2 was safely injected into the fluvial channel sand units of the upper Triassic Stuttgart formation at an approximate depth interval between 630 m and 650 m. The monitoring datasets acquired, including 3D seismic interpretation, electrical resistivity tomography, and borehole temperature and pressure profiling, were largely integrated into the development of a detailed 3D geological model of the reservoir [2]. This was followed by successful history matching of bottomhole pressures and CO_2 arrival times at the injection and observation wells in the near field region [3]. Additionally, in view of the transition to the post-closure phase at Ketzin, long-term simulation studies were carried out considering the uncertainty in the spatial distribution of the fluvial channels in the far-field region of the reservoir, which in turn leads to uncertainty in the long-term fate of CO_2 in the reservoir [4].

It has been reported that there is currently no indication of high fault slip and dilation tendencies at Ketzin [5], and hence leakage through the major faults present at the top of the anticlinal reservoir structure is highly unlikely. Nevertheless, in order to study its general feasibility, a CO_2 backproduction experiment was conducted from October 15^{th} to October 27^{th} at the Ketzin site [6]. The overarching objective of the experiment, which was carried out under the scope of the EU MiReCOL project [7], was to evaluate whether this technical operation can be used as a corrective measure for pressure management of a storage reservoir. The experiment also aimed to address the questions related to: (a) the behavior of the reservoir and the wellbore during backproduction of CO_2; and (b) the composition of the back-produced gas [6].

During the backproduction experiment, the injection well Ktzi 201 was converted into a producing well to accelerate the pressure reduction in the reservoir. Both CO_2 and brine were back-produced and then heated by a water bath up to ~50°C to avoid the production of dry-ice. Mass flow was regulated manually by a choke manifold. The gas and brine phases were separated and afterwards the gas was vented of into the atmosphere and the brine was stacked in a tank for disposal. The test was conducted continuously over the first week and with an alternating regime including production during day-time and shut-in during night-time in the second week. Production rates of up to 3,200 kg/h, which corresponds to the previous maximum CO_2 injection rate, were tested. A total amount of 240t of CO_2 and 55m^3 of brine was safely retrieved over the two week period. The relevant monitoring parameters included production rates of CO_2 and brine, wellhead and bottomhole pressure and temperature at the production and observation wells and distributed temperature sensing along the production well [6].

The objective of the current study was to numerically assess CO_2 backproduction at the Ketzin site considering two main factors that are closely associated with its feasibility:

- a highly heterogeneous reservoir with existing far-field geological uncertainties; and
- the geomechanical integrity of the production wellbore infrastructure and surrounding rock formation.

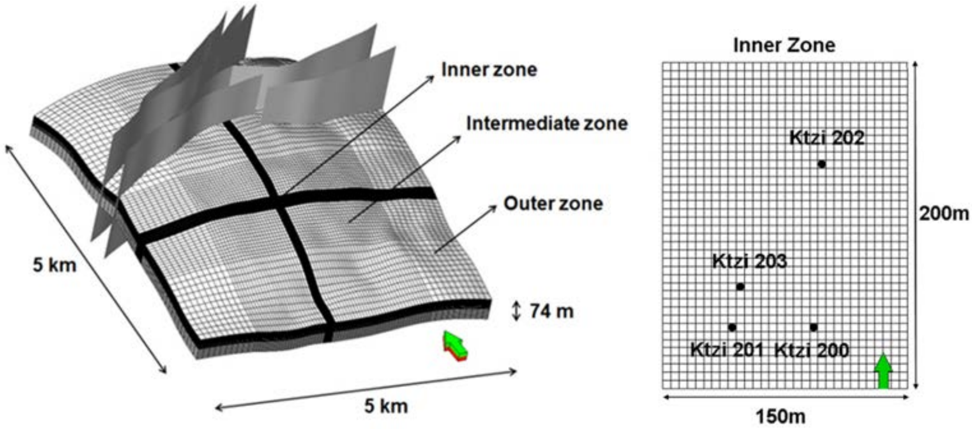
In order to support the numerical studies, CO_2 backproduction rates and bottomhole pressure data from the field experiment were utilised [6]. Additionally, some scenarios were also simulated by altering the backproduction strategies, *e.g.* assuming both constant rates and variable rates, in order to assess the changes in the reservoir pressure during CO_2 backproduction in the near-field region.

For the far-field region of the reservoir, multiple stochastic and equiprobable realisations representing the geological uncertainties were generated, while honouring the facies distribution and petrophysical properties in the near-field region in accordance with the previously history-matched model [3]. A preliminary probabilistic framework based on Markov chain geostatistics [8] was implemented by pooling the long-term predictive results (up to 50 years) of plume migration in the far-field for all the realisations. The key problem being addressed using this framework is to optimise the location of well placement for effective backproduction in the far-field region with existing geological uncertainties.

Furthermore, the changes in stress and pore pressure due to drilling, CO_2 injection and backproduction were used to assess the potential for the development of a failure zone in the near-well region during backproduction using a coupled wellbore model as increased pore pressure may push the Mohr circle beyond the failure envelope and result in shear failure. Excessive pore pressure increase ($p>\sigma_3$) potentially induces tensile failure and thus causing fractures in the reservoir. On the other hand, reducing the pore pressure moves the Mohr stress circle further away from the Mohr failure envelope, which makes failure unlikely.

2. The geological model

The geological model used in this study has a lateral size of 5 km × 5 km and an average thickness of 74 m, and includes seven major faults at the top of the Ketzin anticline. The structural model contains: three lateral discretisation zones - an inner zone of size 150 × 200 m, containing 5 × 5 m grid blocks; an intermediate zone of size 3.5 × 1.5 km, based on the envisaged plume size after a simulation time of 3.5 years, containing 50 × 50 m grid blocks; and an outer zone of size 5 × 5 km containing 100 × 100 m grid blocks; and three vertical discretisation zones (from the top to bottom), namely - Zone A: of about 24 m thickness, containing grid blocks with 0.5 m thickness, in order to account for buoyancy effects (gravity override of CO_2) in a multiphase flow system; Zone B: of about 12 m thickness, containing grid blocks with 2 m thickness; and Zone C: of about 36 m thickness, containing grid blocks with 6 m thickness. Fig. 1(a) illustrates the zones of discretisation in the structural grid. As illustrated in the figure, the seven major bounding faults, with throws of 10 to 30 m, at the top of the anticline are also represented in the model. Additionally, the locations of the backproduction (Ktzi 201) and observation wells (Ktzi 200, Ktzi 202 and Ktzi 203) are annotated in Fig. 1(b).



(a) (b)

Fig. 1. (a) The structural model of the reservoir formation; (b) The location of the injection well (Ktzi 201) and observation wells (Ktzi 200, Ktzi 202 and Ktzi 203) inside the inner zone (after Kempka and Kühn [3]).

The geological model consists of populated facies and petrophysical properties. The facies model has a complex binary distribution, representing the depositional environment inside the Stuttgart Formation in Ketzin, i.e. siltstones and mudstones deposited on a flood plain, in which sandstones of the channel facies are incised. The construction of the model was based on the observed basin-wide characteristics of the Stuttgart Formation as well as site-specific point and spatial data, as discussed in more detail by Norden and Frykman [2]. The porosity values were populated using Sequential Gaussian Simulation (SGS). The porosity estimation is based on separate variogram functions for the channel and floodplain facies, determined using the petrophysical core and log data available from the site [9]. The permeability model was estimated using deterministic and empirical porosity-permeability relationships for the different facies types [10]. The permeability distribution was further calibrated by Kempka and Kühn [3] to carry out the history matching for well bottomhole pressures (BHPs) and plume arrival times at the two observation wells Ktzi 200 and 202. A detailed description of the reservoir simulation parameters are available in [3,11].

3. Numerical modelling of backproduction at Ketzin site

3.1. CO_2 backproduction modelling and history matching of the field experiment

The backproduction simulations were set up in Schlumberger's ECLIPSE 300 (E300) software using the geological model and dynamic reservoir parameters based on previous studies carried out by Kempka and Kühn [3]. The history-matched results obtained for gas saturation and bottomhole pressures during the CO_2CARE project [4] for the CO_2 injection period at Ketzin (June 2008 - August 2013), as illustrated in Fig. 2 and Fig. 3 respectively, were used in order to assume the initial reservoir condition prior to backproduction.

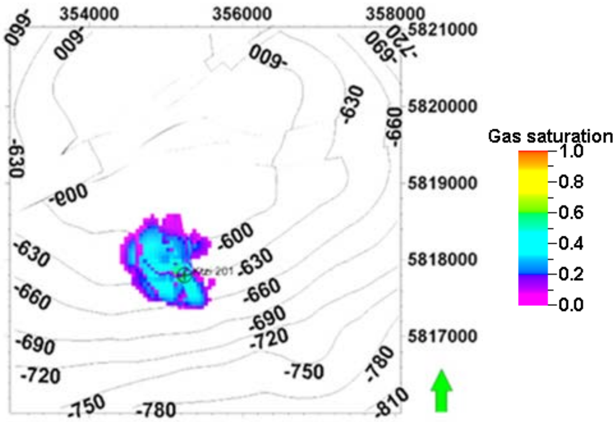


Fig. 2. Simulated gas saturation distribution at the end of injection (August 2013) at Ketzin; the contour lines indicate the depth of the top surface of the reservoir model.

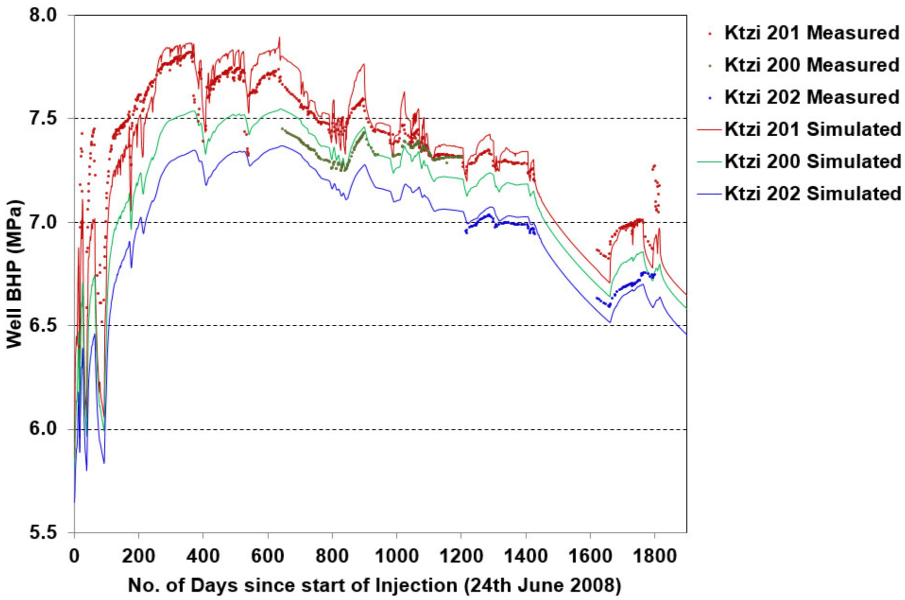
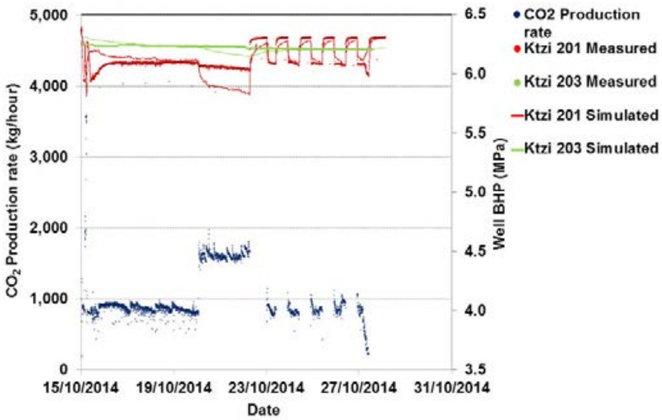
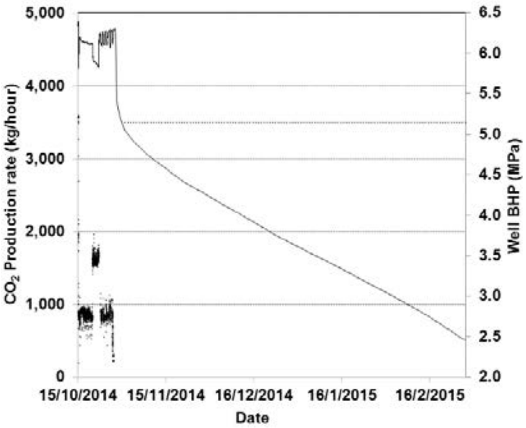


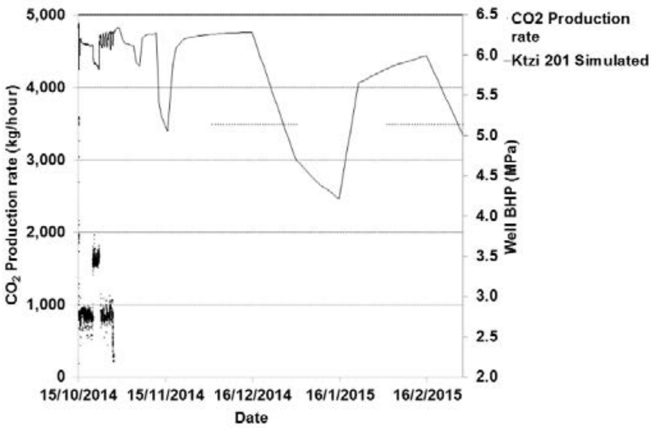
Fig. 3. Comparison of measured (dotted lines) and simulated (solid lines) well BHPs during CO_2 injection at Ketzin.



(a)



(b)



(c)

Fig. 4. (a) Comparison of the measured (dotted lines) and simulated (solid lines) well BHPs during CO_2 backproduction at Ketzin; (b) Simulated long-term well BHP at Ktzi 201 for a scenario considering CO_2 backproduction at a constant rate of 3,500 kg/hour; (c) Simulated long-term well BHP at Ktzi 201 for a scenario considering CO_2 backproduction at a variable rate (switching between 0 and 3,500 kg/hour).

The CO_2 backproduction rates (in kg/hour) were implemented and the model was simulated for the actual period of field operation of 14 days. It was noted that the bottom-hole temperature data did not show much variation during this period, with average values of 29.5°C and 33°C at Ktzi 201 and Ktzi 203 respectively. The history matching results for the bottom-hole pressures at the wells and CO_2 production rates obtained are illustrated in Fig 4a. In addition, two scenarios were subsequently assumed for extended periods of CO_2 backproduction (for four months, until March 2015) including: (a) constant production rate, assumed at a peak rate of 3,500 kg/hour; and (b) variable production rate, switching periodically between 0 and 3,500 kg/hour every month. The simulated bottom-hole pressures at Ktzi 201 for these scenarios indicate that the decrease in pressure would range between 1-4 MPa for a longer period of backproduction (Figs. 4b and 4c).

3.2. Assessment of backproduction in the far-field region

In the presence of geological uncertainties, and assuming that additional seismic or geoelectric surveys at Ketzin are not likely to be carried out 50 years after site abandonment, it may be particularly challenging to select a drilling location for a new CO_2 backproduction well, should the need arise. In this study, this decision-making problem was approached by the development of a preliminary probabilistic framework based on the theory of Bayesian Markov chain random field (MCRF) [8]. It was assumed that, in the far-field, most of the CO_2 plume rises to the top layer of the reservoir due to buoyancy, and thus the current evaluation is carried out in 2D.

Initially, the geological uncertainties in the far-field region were represented by generating multiple realisations of the fluvial channels system that honour the near-field data using the stochastic object modelling, as previously illustrated by the authors in [4] and described briefly in the previous section. CO_2 injection and relaxation simulations were then carried out for all the realisations. The predictive results obtained were subsequently used as training data to learn the conditional probabilities associated with plume migration in the channel and interchannel facies of the far-field region. Additionally, channel-to-interchannel transition probability diagrams (or transiograms) were also estimated for all the realisations. The algorithm implemented may be summarised in two steps:

- 'Model' likelihood estimation using the plume conditional probabilities:

$$P(Plume \mid Model) = \sum_{Z \in \{1,0\}} P(Plume \mid Z, Model) P(Z) \quad (1)$$

- Posterior estimation using the facies transition probabilities of the maximum likelihood model:

$$P(Z=1 \mid X=1, Y=1) = \frac{P(X=1 \mid Z=1) P(Z=1 \mid Y=1)}{\sum_{Z \in \{1,0\}} P(X=1 \mid Z) P(Z \mid Y=1)} \quad (2)$$

where, X and Y are sets of reference points in the near-field region along the EW and NS directions respectively, Z is the point of estimation in the far-field region, for all X, Y, Z ∈ {1 = Channel, 0 = Interchannel}, and 'Model' stands for a particular instance of the set of equiprobable realisations in the training dataset.

The algorithm was executed for all the locations in the far-field region, and an optimal location corresponding to the maximum posterior probability of the channel facies type was determined. Fig 5(a) indicates location A as the optimal solution obtained, and the two neighbouring sub-optimal locations B (350 m from A) and C (600 m from A). A comparison was made between these locations based on the cumulative amount of CO_2 backproduced, when subjected to the original production regime used at Ktzi 201 well during the field experiment. The cumulative amount produced at location A is 240 tonnes of CO_2, while only fractional (sub-optimal) amounts of CO_2 are produced from locations B and C, estimated at 16% and 5% of the cumulative amount at location A respectively (Fig. 5(b)).

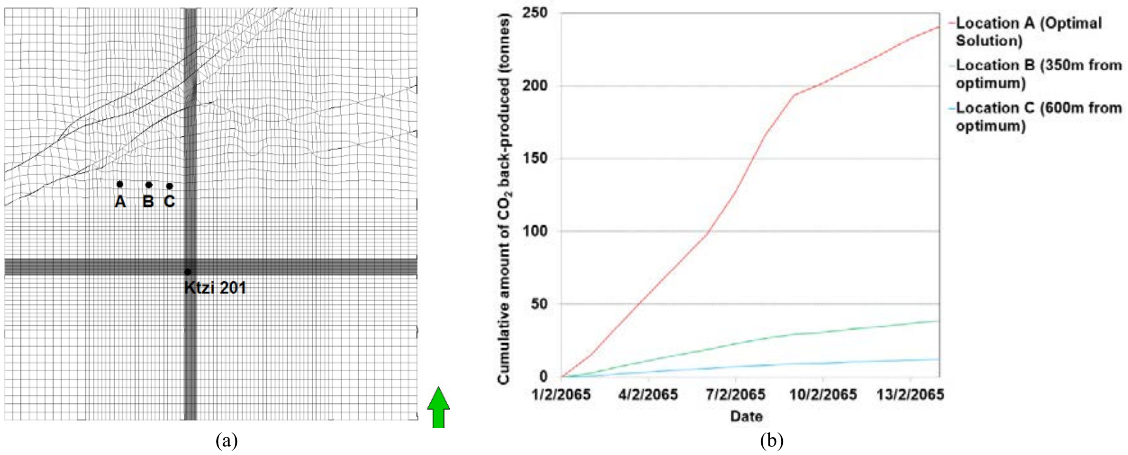


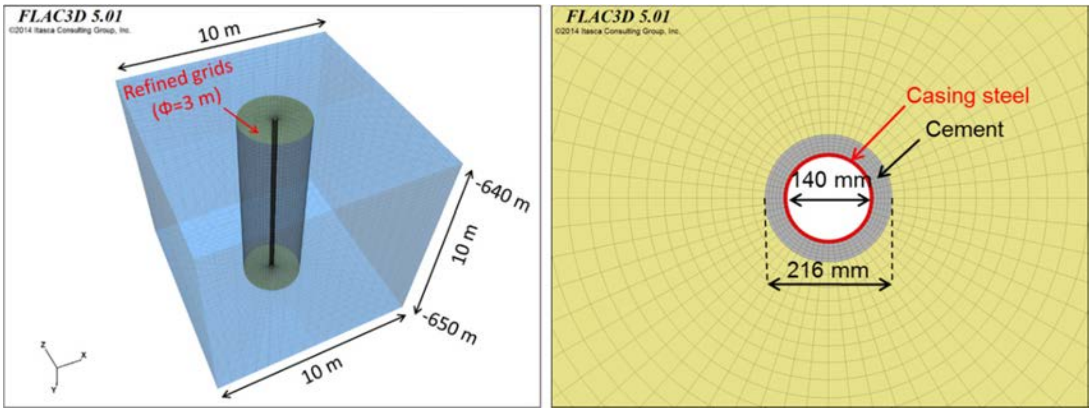
Fig. 5. (a) Optimal (A) and sub-optimal locations (B and C) in the far-field if backproduction is considered after 50 years of site abandonment; (b) Comparison of the amounts of back-produced CO_2 between the optimal and sub-optimal locations in the far-field region.

4. Near wellbore geomechanical model for the Ketzin site

The wellbore model developed aims at assessing the potential for failure zone development in the near-well region during backproduction at the Ketzin site. As reported earlier, since the well bottomhole temperature monitoring data suggested that there was no significant temperature change during backproduction, only the effect of pressure change on near wellbore behaviour was considered in the model. As described earlier, the history-matched results obtained for gas saturation and bottomhole pressures for the CO_2 injection period at Ketzin were used in order to assume the initial reservoir condition prior to backproduction.

In order to assess the near wellbore stress and failure behaviour during backproduction, a geomechanical model was setup in FLAC3D software. As shown in Fig. 6(a), the physical dimensions of the model are 10×10×10m (length×width×height) and a cylindrical zone at the centre of the model is refined to accommodate the simulated wellbore. Fig 6(b) shows the detailed model design of the near wellbore, which covers two concentric rings of cement and casing. The entire model domain was assumed to be within the Stuttgart formation at depth from -640 to -650 m.

In the model, σ_v is assumed to be the intermediate principal stress and its magnitude is close to the load induced by the overburden weight (15.1 MPa). As reported by Klapperer *et al*. [12], the maximum principal stress σ_H is in NE-SW direction, parallel to the axis of the anticline. The magnitude of σ_H and σ_h are suggested to be lower than 2.8 σ_v and higher than 0.62σ_v, respectively. Therefore, σ_H and σ_h are assumed to be the maximum (42.3 MPa) and minimum (9.4 MPa) values at each range. Y-axis was assumed to be the vertical direction, z-axis (positive) was assumed to be pointing the North, and the angle between σ_H and z-axis is 60°. The boundary conditions of the model were such that it is laterally confined and the model base is fixed.



(a) (b)

Fig. 6. (a) The wellbore model geometry; (b) Central refined area.

Material properties used in this model (Table 1) were adopted from Ouellet *et al*. [13]. The constitutive model used was the classical Mohr-Coulomb model in FLAC3D. Cement and casing steel were modelled as elastic and their properties are taken from the literature [14]. The initial reservoir pore pressure was assumed to be uniform at 6 MPa within the model domain.

Table 1. Rock mechanical and strength properties of the Stuttgart formation and the wellbore material.

Layer	K (GPa)	G (GPa)	φ (°)	C (MPa)	t (MPa)
Stuttgart formation	6.06	3.13	25	11.47	-1.15
Cement	19.43	6.14	-	-	-
Casing steel	160.31	80.47	-	-	-

The simulation consists of five consecutive steps: (1) initial equilibrium; (2) drilling; (3) well completion; (4) CO_2 injection; and (5) CO_2 backproduction. Drilling was simulated in the model by assigning the 'NULL' property (no mechanical stiffness and strength) to the grids representing the well at 216 mm diameter. In the well completion stage, the grids representing the cement and casing were reinstated and the well diameter was reduced to 140 mm. The coupling between casing and cement, and cement and rock were assumed to be fully bonded.

The stress distribution and failure zones modelled after well completion formed the baseline conditions for the analysis of CO_2 injection/backproduction processes. At this stage, shear failure was seen in the large compressive stress zone and tensile failure was found in the stress relief zone. Note that the well completion process had no impact on the development of near wellbore failure zone. Next, the near wellbore stress and failure behaviour during the CO_2 injection phase was evaluated. The pore pressure within the model domain was gradually elevated from 6 MPa to 8 MPa to simulate the CO_2 injection process. It was observed that, compared to the pre-injection period, the failure zone near the wellbore increased slightly with the increase of CO_2 injection pressure (Figs. 7(a) and (b)). In the meantime, the percentage of failure zone volume within the refined area was recorded at different pressure levels (Fig. 7(c)).

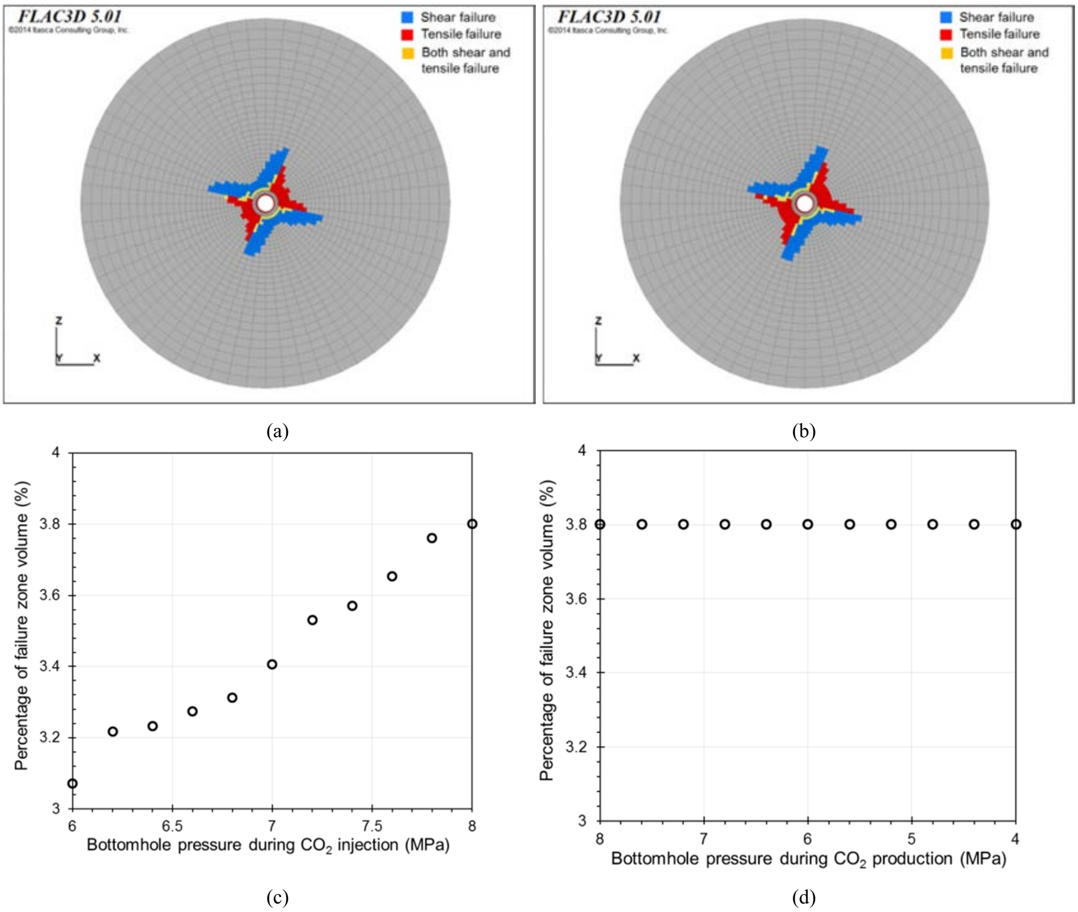


Fig. 7. (a) Distribution of the near wellbore failure zone when the CO_2 injection pressure is 7 MPa; (b) Distribution of the near wellbore failure zone when the CO_2 injection pressure is 8 MPa; (c) Failure zone development during the CO_2 injection process; (d) Failure zone development (or lack of it) during the CO_2 backproduction process.

The wellbore model was subsequently used to reduce the pore pressure gradually from 8 MPa to 4 MPa to mimic the period of CO_2 back production. Fig. 7(d) illustrates that, under near constant temperature conditions experienced at Ketzin, decreasing the near wellbore pore pressure has almost no effect on the failure zone developed earlier, and its size remains the same after CO_2 backproduction.

5. Conclusions

CO_2 backproduction is considered to be one of alternative remedial measures available for operators, should a significant irregularity occur in the storage reservoir, namely an unpredicted and undesired migration of the plume or an unexpected increase in reservoir pressure, during the injection or post-injection periods. As part of the research activities on leakage risk mitigation and remediation techniques under the scope of the EU MiReCOL project, the technical feasibility of backproduction was successfully tested at the Ketzin pilot site.

In this paper, the field backproduction experiment data was history matched and the process was evaluated first. Additional scenarios were also modelled for extended periods of backproduction with a view of understanding the pressure variation and its effect on the geomechanical integrity of the wellbore infrastructure. The modelling results demonstrate that, while the failure zones develop for a small estimated percentage of 3.8% of the volume of the near wellbore region during the injection period, it remains fairly constant for the simulated scenarios where the decrease in pressure reaches up to 4MPa during the backproduction period.

Considering the far-field region of the Ketzin reservoir, where geological uncertainties exist, occurrence of significant irregularities in plume behaviour, say after 50 years of post-closure period, would call for a new drilling location to back-produce CO_2. Under the assumption that no seismic or geoelectric monitoring data would be available to support such a decision-making process, a probabilistic approach based on Bayesian Markov chain random field (MCRF), which provides optimal drill locations, is proposed in this paper. The backproduction results obtained thusfar are promising. However, the far-field assessment was carried out in 2D, and its extension to 3D is currently under development.

Acknowledgements

The research reported in this paper was conducted as part of the European Commission FP7 funded project MiReCOL (www.mirecol-co2.eu), Grant Agreement No: 608608, and the COMPLETE project jointly funded by the German Federal Ministry of Education and Research and VGS, RWE, Vattenfall, Statoil, OMV and the Norwegian CLIMIT programme.

References

[1] Martens S, Moeller F, Streibel M, Liebscher A, and the Ketzin Group. Completion of five years of safe CO_2 injection and transition to the post-closure phase at the Ketzin pilot site. Energy Procedia 2014; 59:190-197.

[2] Norden B, Frykman P. Geological modelling of the Triassic Stuttgart Formation at the Ketzin CO_2 storage site, Germany. Int. J. Greenh. Gas Control 2013; 19:756-774.

[3] Kempka T, Kühn M. Numerical simulations of CO_2 arrival times and reservoir pressure coincide with observations from the Ketzin pilot site, Germany. Environ. Earth Sci 2013; 70:3675-3685.

[4] Govindan, R, Babaei, M, Korre, A, Shi, J-Q, Durucan, S, Norden, B, Kempka, T. CO_2 Storage Uncertainty and Risk Assessment for the Post-closure Period at the Ketzin Pilot Site in Germany. Energy Procedia 2014; 63:4758-4765.

[5] Kempka T, De Lucia M, Kühn M. Geomechanical integrity verification and mineral trapping quantification for the Ketzin CO_2 storage pilot site by coupled numerical simulations. Energy Procedia 2014; 63:3330-3338.

[6] Martens, S, Kempka, T, Liebscher, A, Möller, F, Schmidt-Hattenberger, C, Streibel, M, Szizybalski, A, Zimmer, M. Field experiment on CO_2 back-production at the Ketzin pilot site. Energy Procedia 2015; 76:519-527.

[7] Neele, F, Grimstad, A.A, Fleury, M, Liebscher, A, Korre, A, Wilkinson, M. MiReCOL: Developing Corrective Measures for CO_2 Storage. Energy Procedia 2014; 63:4658-4665.

[8] Li, W, Zhang, C. A single-chain-based multidimensional Markov chain model for subsurface characterization. Environ. Ecol. Stat. 2008; 15(2):157-174.

[9] Norden, B, Förster, A, Vu-Hang, D, Marcelis, F, Springer, N, Le Nir, I. Lithological and petrophysical core-log interpretation in CO2SINK, the European CO_2 onshore research storage and verification project. SPE Reservoir Eval Eng 2010; 13:179-192.

[10] Kempka T, Class H, Görke U-J, Norden B, Kolditz O, Kühn M, Walter L, Wang W, Zehner B. A Dynamic Flow Simulation Code Intercomparison based on the Revised Static Model of the Ketzin Pilot Site. Energy Procedia 2013; 40: 418-427.

[11] Kempka T, Kühn M, Class H, Frykman P, Kopp A, Nielsen CM, Probst P. Modelling of CO_2 arrival time at Ketzin–Part I. . Int J Greenh Gas Control 2010; 4(6):1007-1015.

[12] Klapperer, S, Moeck, I, Norden, B. Regional 3D Geological Modeling and Stress Field Analysis at the CO_2 Storage Site of Ketzin, Germany. Geothermal Resources Council Transactions 2011; 35:419-424.

[13] Ouellet, A, Bérard, T, Desroches, J, Frykman, P, Welsh, P, Minton, J, Pamukcu, Y, Hurter, S, Schmidt-Hattenberger, C. Reservoir geomechanics for assessing containment in CO_2 storage: A case study at Ketzin, Germany. Energy Procedia 2011; 4:3298-3305.

[14] BGS. A joint research project report on "Reactions between CO_2 and borehole infrastructure" by British Geological Survey, Imperial College, IFP Energies Nouvelles and Bureau de Recherches Géologiques et Minières. Report submitted to European Commission during the CO2GeoNet project 2008.