Journal of Energy Challenges and Mechanics
http://www.nscj.co.uk/JECM/
ISSN 2056-9386
Volume 1 (2014) issue 4, article 4

Impact of temperature on CO_2 storage in a saline aquifer based on fluid flow simulations and seismic data (Ketzin pilot site, Germany)

基于流体模拟和地震数据（德国 Ketzin 试点）研究温度对咸水层二氧化碳封存的影响

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Accepted for publication on 28th November 2014

Abstract - **Temperature is one of the main parameters influencing CO_2 properties during storage in saline aquifers, since it controls along with pressure the phase behavior of the CO_2/brine mixture. When CO_2 replaces brine as a free gas it is known to affect the elastic properties of porous media considerably. In order to track the migration of geologically stored CO_2 in a saline aquifer at the Ketzin pilot site (Germany), 3D time-lapse seismic data were acquired by means of a baseline (pre-injection) survey in 2005 and monitor surveys in 2009 and 2012. At Ketzin, CO_2 was injected from 2008 to 2013 in a sandstone reservoir at a depth of about 630 - 650 m. In total about 67 kilotons of CO_2 were injected. The present study is devoted to the 4D seismic dataset of 2005 - 2009. The temperature in the storage reservoir near the injection well was observed to have increased from 34 °C in 2005 to 38 °C in 2009. This temperature increase led us to investigate the impact of temperature on the seismic response to CO_2 injection and on our estimations of spatial CO_2 mass distribution in the reservoir based on the Ketzin 4D seismic data. Both temperature scenarios in the reservoir of 2005 and 2009 were studied using multiphase fluid flow modeling. The isothermal simulations carried out for both 34°C and 38°C show that the impact of temperature on the seismic response is minor, but the impact of temperature on the CO_2 mass estimations is significant. The multiphase fluid flow simulations show a strong temperature impact on CO_2 density stressing the need for temperature monitoring in a CO_2 storage reservoir to support quantitative observations in the storage complex.**

Keywords – **CO_2 storage, Seismic modeling, Multiphase flow, Reservoir temperature.**

I. Introduction

It is well known that temperature along with pressure are the major parameters influencing CO_2 storage (e.g. [1], [2]). However, only few experimental data are reported in the temperature and pressure range of interest [2, 3]. At the Ketzin pilot site in Germany [4], CO_2 was injected from 2008 to 2013 at about 640 m depth with the temperature data being continuously acquired with a permanently installed system [5]. Ketzin is the first European onshore pilot scale project for CO_2 storage in a saline aquifer [4]. This storage site is situated on an anticlinal structure hosting sandstones of the heterogeneous Triassic Stuttgart Formation [4] which serve as a reservoir. These sandstones vary in thickness between 15 and 30 m [4] at the injection site. The CO_2 storage reservoir is sealed by an approximately 200 m thick cap rock section of playa-type mudstones of the Weser and Arnstadt Formations [4]. Totally about 67 kilotons of CO_2 were injected at Ketzin. A number of reservoir simulations have been performed to enhance the understanding of CO_2 migration at the Ketzin pilot site [4, 6]. Reservoir simulations and 4D seismic data analysis were successfully integrated at the Sleipner CO_2 storage site [7]. This motivated us to integrate these two methods also at the Ketzin pilot site. 3D time-lapse seismic data were acquired by means of a baseline (pre-injection) survey in 2005 [8] and two monitor surveys in 2009 [9] and 2012 [10]. The present study is devoted to the 4D seismic dataset of 2005 - 2009. The 3D baseline seismic survey [8] at the Ketzin pilot site revealed a sequence of clear reflections from approximately 150 ms to 900 ms two-way traveltime in the stacked volume. In 2009, a subset of this baseline survey was acquired around the injection well after approximately 22–25 kilotons of CO_2 had been injected [9]. This 3D seismic repeat survey showed a pronounced time-lapse amplitude anomaly at the top of the storage reservoir [9] demonstrating that CO_2 can be monitored under such conditions. As a follow up, CO_2 seismic signatures were used to make estimates on imaged amount of injected CO_2. These estimates were done in [9] neglecting the impact of the reservoir temperature. However the temperature increased by 4° by 2009 due to the injection [3]. At the same time there was no significant change in the values of the reservoir temperature 50 m and 112 m away from the injection well [3]. Based on these observations, it appears likely that the CO_2 density was 260 kg/m3 at the injection point (38°C) in 2009, whereas it was near 320 kg/m3 in the more distant part of the plume, close to the ambient temperature (34°C) [3]. In order to investigate the impact of the reservoir temperature variation on the interpretation of the 4D seismic data at Ketzin, we deduce quantitative CO_2 mass estimates for the both reservoir temperature values in 2009 (34°C and 38°C). In the first step we apply seismic forward modeling using so far established petrophysical models for the Ketzin reservoir sandstone [3]. Subsequently, CO_2 mass estimations based on reservoir isothermal simulations for both temperature scenarios are compared to other ones obtained by the in situ CO_2 saturation logging in [9].

II. Multiphase Fluid Flow Simulations

We apply in this study 2D multiphase fluid flow simulations to account for the lateral variability in the petrophysical properties of the storage formation at Ketzin and, in turn, on the 4D seismic data regarding the impact of the reservoir temperature on the fluid migration. Hydrogeological studies at the Ketzin pilot site [11] have shown that a 2D radially symmetric model of the upper part (33 m) of the Stuttgart Formation can be used to interpret the 3D data acquired near the injection well. This model accounts for the presence of channel sandstones in the reservoir that are the most favorable for CO_2 migration and contains effective porosities in the range of 20–25% [4]. Initial reservoir conditions and rock properties within the reservoir sandstone and the surrounding mudstone are listed in Table 1 [3]. They were assumed to be spatially constant for the flow simulations, which were performed using the numerical program TOUGH2 version 2.0 [12] with the fluid property module ECO2N, which was designed for application to the geologic storage of CO_2 in saline aquifers [13]. Two isotherm cases were considered with a constant reservoir porosity of 20%, one where the reservoir temperature is 34°C and the other where the reservoir temperature is 38°C (Table 1).

The resulting simulated CO_2 saturation does not differ significantly between the two scenarios (less than 5%), whereas the CO_2 density is notably lower for the higher temperature case (Fig. 1). In the vicinity of the injection well, the difference in CO_2 density is up to 20% and on average 12%.

TABLE 1, Material properties and initial conditions used for multiphase fluid flow simulations [3]

Material Property		
Porosity [-]	0.20	
Horiz. perm. [m²]	$80 \cdot 10^{-15}$	
Vertic. perm. [m²]	$26.7 \cdot 10^{-15}$	
Residual liquid saturation S_{lr} [-]	0.15	
Residual gas saturation S_{gr} [-]	0.05	
Initial Conditions		
Pressure [MPa]	6.28	
Temperature [°C]	34	38
Salinity [wt.-% NaCl]	20.0	

III. Qualitative Impact of Reservoir Temperature on Seismic Data

In order to investigate the impact of temperature in the reservoir on the 4D seismic data at the Ketzin pilot site, CO_2 saturation and CO_2 density, as well as the thickness of the CO_2 layer obtained by multiphase fluid flow simulations are used as input to seismic modeling [3]. The forward seismic modelling was done for three points: the injection well and two other points, distanced 50 m and 112 m away from the injection well (Fig. 1).

The resulting synthetic seismic differences of both the 34°C and 38°C options look very similar [3]. The synthetic difference (repeat-base) seismograms from near the top of the reservoir agree reasonably well with the real difference seismograms (repeat-base) for the injection well and for the distance of 50 m away from this well [3]. However, obvious disagreements are found 112 m away from the injection well, may be because the velocity model from [3] for this location is too simplified. Seismic amplitude differences between the 38°C and 34°C scenarios correspond to less than 1% of the amplitude values of the baseline. Since the normalized root mean square differences in the 3D time-lapse data are greater than 10% [3] these temperature effects in the reservoir will not be resolvable with surface seismic methods at the Ketzin pilot site.

IV. Quantitative Impact of Reservoir Temperature on Seismic Data

Although it is not possible to determine the reservoir temperature from the seismic amplitude at the Ketzin pilot site in 2005 and 2009, we are able to study here the impact of the reservoir temperature on quantitative interpretation of the seismic data [3]. We apply the method of volumetric estimation of [9] to both the 34°C and 38°C reservoir temperature scenarios and estimate the mass of the injected CO_2 based on the above simulations.

As in [9] we put the minimum and maximum bounds in our quantification at the beginning and end of the 3D seismic repeat acquisition campaign in 2009 at Ketzin. The minimum total mass (25.6 kilotons) and the maximum total mass (29.3 kilotons) for the 34°C scenario are considerably higher than the amount of injected CO_2 at the time of the repeat survey in 2009 (21.1–24.2 kilotons). However, for the 38°C option, the

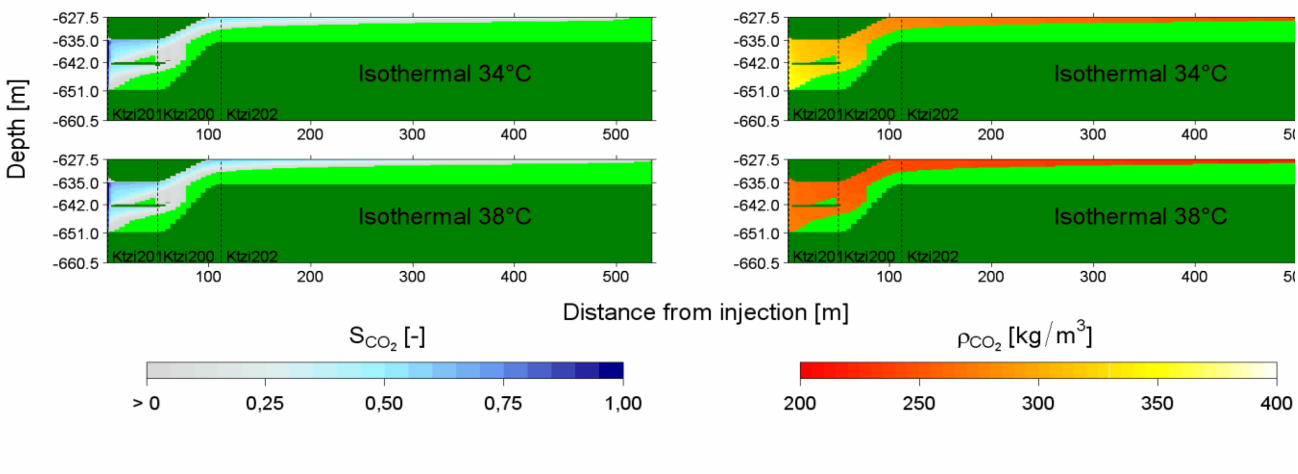

Fig.1, Simulated distributions of CO_2 saturation (left panel, blue scale) and density (right panel, yellow–orange scale) with an isothermal temperature of 34°C and 38°C for October 28, 2009 [3]. CO_2 free rocks of the Stuttgart Formation are dark green. Parts of this formation saturated with brine only are indicated with the light green color. "Ktzi201" is the injection well. "Ktzi200" and "Ktzi202" are observation wells distanced 50 m and 112 m away from the injection well respectively [4].

minimum mass (22.3 kilotons) and maximum mass (22.8 kilotons) are completely within the bounds of the amount of injected CO_2 (21.1–24.2 kilotons) and match well with the CO_2 mass estimation from [9] (20.5–23 kilotons). This quantification shows that the impact of the reservoir temperature is considerable when trying to quantify the amount of CO_2 in the subsurface and that it needs to be accurately estimated. Based on this quantification it appears that a significant portion of the reservoir containing CO_2 was at 38°C at the time of the 3D seismic repeat survey in 2009.

III. Discussion

It is likely that in 2009 the simulated scenarios of 38°C and 34°C are representative in the vicinity of the injection well and in the remaining reservoir, respectively. This is based on a measured temperature of approximately 38°C at the injection well in 2009, while at the observation wells distanced 50 m and 112 m away from the injection well the temperature was at 34°C. Since most of the CO_2 was concentrated around the injection well in 2009, the higher temperature value plays an important role in estimating the mass of CO_2 from the seismic data of the real difference seismograms (repeat-base) [3]. The integration of seismic modeling and multiphase fluid flow simulations allows for synthetic time-lapse difference seismograms (repeat-base) that demonstrate the main features of the real seismic data. Taking into account assumptions made constructing the model we consider the correlation between the synthetic and real seismic sections to be satisfactory. But the following points should be considered when evaluating the modeling results. The constant 20% reservoir porosity [3] used for modeling of the temperature effects is probably an over-simplification since the reservoir is quite heterogeneous [4]. In addition, sound waves may have a frequency dependent propagation velocity so that the higher the frequency the higher the speed. Although velocity dispersion is probably present in the Ketzin reservoir sandstones, we do not consider it to be large enough that it could considerably affect the qualitative and quantitative interpretation of our time-lapse seismic data [9].

Besides, our seismic interpretation of the time-lapse 3D dataset 2005-2009 contains an uncertainty contributed by experiments on core samples at 40°C, because temperature in the reservoir at Ketzin was 34°C before the injection and 34-38°C in 2009, respectively. After [14] and [15] temperatures near the CO_2 critical point have just a minor effect on the seismic velocity in sands saturated with brine and CO_2. Via the Gassmann's equations [16] this translates into 9 m/s as the maximum change in Vp between the options of 34°C and 40°C. Therefore, this effect can be disregarded.

The estimation of the CO_2 mass based on the Ketzin 4D seismic data shows that the impact of temperature is significant for the calculations due to its impact on CO_2 density. Hence, temperature monitoring is an important component for quantitative seismic interpretations at a saline aquifer. Using the temperature measured at the injection well at Ketzin in 2009 for the mass estimation results in a better CO_2 mass quantification. This result is completely within the bounds of the known injected CO_2 mass at the beginning and end of 3D seismic repeat acquisition campaign and in very good agreement with the CO_2 mass estimation based on in situ CO_2 saturation logging. Nevertheless, it has to be taken into consideration that the quantitative analysis contains considerable uncertainties as discussed above and in [9].

Future issues to be considered include expanding the temperature range (34–38°C in this study) to be investigated and the resulting effects on the seismic response and the role of the reservoir heterogeneity. It would be also important to investigate the impact of temperature on CO_2 storage at other sites with favorable P-T conditions in the reservoir. A similar approach applied to the impact of pressure in the reservoir would also be important for CO_2 monitoring using 3D time-lapse seismic methods.

IV. Conclusions

By integrating seismic modeling and multiphase fluid flow simulations, we have estimated the impact of temperature in the reservoir on 4D seismic data from Ketzin. We studied two options, one where the injection was performed at 34°C and the other at 38°C. Results from the multiphase fluid flow simulations show that the difference between these options is small for the CO_2 migration. Likewise, the temperature does not affect significantly the seismic amplitude response, in spite of the fact that CO_2 density is considerably lower for the higher temperature case. Therefore, the modeled time-lapse seismic differences for the two temperature scenarios show that the effect of reservoir temperature is minor for the qualitative analysis of the 4D seismic data from the Ketzin pilot site.

However, the CO_2 mass quantification based on the 4D seismic data from Ketzin using results from the multiphase fluid flow simulations shows that the impact of temperature in the reservoir at the monitoring time is significant for such quantification. This is mostly due to the impact on CO_2 density, which strongly depends on temperature. The simulated CO_2 saturation levels also influence volumetric estimation. The results show that temperature monitoring is very important for quantitative seismic interpretation at the Ketzin pilot site. Using the higher temperature scenario, corresponding to that measured at the injection well, gives a better result for the CO_2 mass. This estimate is completely within the bounds of the true amount of injected CO_2.

V. Acknowledgement

The European Commission (6th and 7th Framework Program), two German ministries - the Federal Ministry of Economics and Technology and the Federal Ministry of Education and Research - and industry are gratefully acknowledged for funding the Ketzin pilot project since 2004. The ongoing activities are funded within the project COMPLETE by the Federal Ministry of Education and Research within the GEOTECHNOLOGIEN program (this is publication GEOTECH-2217). Further funding is received from VGS, RWE, Vattenfall, Statoil, OMV and the Norwegian CLIMIT programme.

References

[1] A. Kumar, M. Noh, G.A. Pope, K. Sepehrnoori, S. Bryant, and L.W. Lake. “Reservoir Simulation of CO_2 Storage in Deep Saline Aquifers,” *SPE J.*, **10**(3), pp. 336-348, 2005.

[2] S. Bachu, and D.B. Bennion. “Dependence of CO_2-brine interfacial tension on aquifer pressure, temperature and water salinity,” *Energy Procedia*, **1** (1), pp. 3157-3164 GHGT-9, 2009.

[3] A. Ivanova, C. Juhlin, U. Lengler, P. Bergmann, S. Lüth, and T. Kempka. “Impact of temperature on CO_2 storage at the Ketzin site based on fluid flow simulations and seismic data,” *International Journal of Greenhouse Gas Control*, 19, pp. 775-784, 2013.

[4] S. Martens, T. Kempka, A. Liebscher, S. Lüth, F. Möller, A. Myrttinen, B. Norden, C. Schmidt-Hattenberger, M. Zimmer, M. Kühn, and The Ketzin Group. “Europe's longest-operating on-shore CO_2 storage site at Ketzin, Germany: a progress report after three years of injection”, *Environmental Earth Sciences*, **67** (2), pp. 323-334, 2012.

[5] J. Henninges, A. Liebscher, A. Bannach, W. Brandt, S. Hurter, S. Köhler, F. Möller, and CO2SINK Group. “P-T-ρ and two-phase fluid conditions with inverted density profile in observation wells at the CO_2 storage site at Ketzin (Germany)”, *Energy Procedia*, **4**, pp. 6085-6090, 2011.

[6] T. Kempka, and M. Kühn. “Numerical simulations of CO_2 arrival times and reservoir pressure coincide with observations from the Ketzin pilot site, Germany”, *Environmental Earth Sciences*, Special Issue, pp. 1–11, doi:10.1007/s12665-013-2614-6, 2013.

[7] R. Arts, O. Eiken, A. Chadwick, P. Zweigel, L. van der Meer, and B. Zinszner. “Monitoring of CO_2 injected at Sleipner using time lapse seismic data” *Energy*, **29**, pp. 1383-1392, 2004.

[8] C. Juhlin, R. Giese, K. Zinck-Jørgensen, C. Cosma, H. Kazemeini, N. Juhojuntti, S. Lüth, B. Norden, and A. Förster. “3D baseline seismics at Ketzin, Germany: the CO2SINK project”, *Geophysics*, **72**, pp. 121-132, 2007.

[9] A. Ivanova, A. Kashubin, N. Juhojuntti, J. Kummerow, J.Henninges, C. Juhlin, S. Lüth, and M. Ivandic. “Monitoring and volumetric estimation of injected CO_2 using 4D seismic, petrophysical data, core measurements and well logging: a case study at Ketzin, Germany”, *Geophysical Prospecting*, **60**(5), pp. 957-973, 2012.

[10] M. Ivandic, C. Juhlin, S. Lüth, P. Bergmann, A. Kashubin, D. Sopher, A. Ivanova, G. Baumann, and J. Henninges. “Geophysical monitoring at the Ketzin pilot site for CO_2 storage: New insights into the plume evolution”, *International Journal of Greenhouse Gas Control*, submitted, 2014.

[11] B. Norden, A. Förster, D. Vu-Hoang, F. Marcelis, N. Springer, and I. Le Nir. “Lithological and petrophysical core-log interpretation in CO2SINK, the European CO_2 Onshore Research Storage and Verification Project”, *SPE Reservoir Evaluation & Engineering*, **13** (2), pp. 179-192, 2010.

[12] K. Pruess, C. Oldenburg, and G. Moridis. ”TOUGH2 User's guide, Version 2.0”, *Lawrence Berkeley National Laboratory Report LBNL-43134*, Berkeley, USA, 1999.

[13] K. Pruess. “ECO2N: A TOUGH2 Fluid Property Module for Mixtures of Water, NaCl, and CO_2“, *Lawrence Berkeley National Laboratory Report LBNL-57952*, Berkeley, USA, 2005.

[14] G. Mavko. “Parameters That Influence Seismic Velocity”*http://pangea.stanford.edu/courses/gp262/Notes/8.SeismicVelocity.pdf*, 2005.

[15] D. Han, M. Sun, and M. Batzle. “CO_2 velocity measurement and models for temperatures up to 200 °C and pressures up to 100 MPa”, *Geophysics*, **75** (3), pp. E123–E129, 2010.

[16] F. Gassmann. “Ueber die Elastizitaet poroeser Medien“, *Vierteljahrsschrift der Naturforschenden Gesellschaft Zuerich*, **96**, pp. 1–23, 1951.