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CO_2 storage capacity of a deep aquifer depending on the injection well location and cap rock capillary pressure

Introduction

The view that carbon dioxide is the main factor of global warming and its rising concentration in the atmosphere is a consequence of human activity is gaining increasing acceptance. Actions are undertaken aimed at the reduction of anthropogenic CO_2 emission to the atmosphere. One such action is capturing the CO_2 produced in industrial processes and its underground storage in deep geological structures (Aminu et al. 2017). This action, described as Carbon Capture and Storage (CCS), requires the recognition of geological structures capable of safely and permanently accommodating necessary amounts of the gas. Deep aquifers, depleted hydrocarbon (petroleum and natural gas) deposits and deep, unexploited, coal seams (Gąsiewicz et al. 2010; USDE 2012) are considered as the sites of underground CO_2 storage. Storage in deep aquifers, usually composed of sandstones, offers great volumes for carbon dioxide storage. This is the case not only in Poland where numerous geological

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structures have been recognized as suitable for CO_2 storage (Tarkowski and Uliasz-Misiak 2006; Tarkowski et al. 2009b; Marek et al. 2010). The results of the EU Geocapacity project demonstrate that good recognition is also available all over Europe (Willscher et al. 2008; Tarkowski et al. 2009b; Šliaupa et al. 2013). Installations for carbon dioxide injection: Sleipner on the North Sea and Snøhvit on the Barents Sea (Metz et al. 2006) demonstrate that neutralization of this gas on an industrial scale is now technically feasible and may be profitable.

1. Storage capacity

One of the crucial factors determining the usefulness of a geological structure for underground CO_2 storage is its capacity. This term describes the amount of gas that can be injected into the structure safely and with no side effects for the environment. Carbon dioxide storage capacities are evaluated using various methods. The basic parameters usually used to determine the CO_2 storage capacity of a geological structure include its volume, porosity of the reservoir rock and the values of temperature and pressure in the reservoir horizon. At the early stage of recognition, the volumetric method is used to evaluate the CO_2 storage capacity. The results obtained using this method differ markedly from reality because of the simplified procedure and because of not taking various geological parameters of the deposit into account (Bachu 2015). Only an analysis of the CO_2 storage capacity based on numeric modeling for the given geological structure results in the satisfactory improvement of the evaluation (Hendriks et al. 2004; Bradshaw et al. 2005; 2007). This analysis also allows for taking several injection wells, whose various configurations and various accepted values of injection efficiency have been taken into account, all of which contribute to the increased gas storage capacity (Bachu 2015).

1.1. Influence of capillary pressure on CO_2 storage

The permissible increase in pressure resulting from gas injection to a geological structure is an important factor influencing the CO_2 storage capacity. This is also important, if not the most important, geomechanical parameter of storage safety. It is discussed in two ways: as fracturing pressure (pressure at which a geological structure becomes unsealed) and capillary entry pressure (critical pressure caused by carbon dioxide contained in the underground reservoir/structure), at which supercritical CO_2 penetrates through capillary pores of the sealing cap rocks (Chadwick et al. 2006). The volume calculated using these parameters in numerical calculations is referred to as the “dynamic capacity” (Bachu 2015).

Capillary phenomena are important for the storage of supercritical CO_2. As a non-wetting fluid, supercritical carbon dioxide requires injection at adequately high pressure, sufficient to overcome capillary forces and filling pore spaces and expel brine from them.

Capillary pressure plays an important role in maintaining the tightness of the overburden. As its value is inversely proportional to pore size, very small pores in the rocks of poorly permeable overburden make the cap rocks resistant to capillary migration of supercritical CO_2 (Tokunaga and Wan 2013).

During carbon dioxide injection into a reservoir layer, in consequence of the density difference between water (brine) and supercritical CO_2, the latter tends to rise and accumulate in large amounts directly below the impermeable roof and thus leads to an increase in pressure relative to the initial pressure in the structure. The upward movement of the CO_2 through the pore system is resisted by capillary pressure. As long as this pressure increase is not exceeded, the caprock remains tight for the gas. When the value of the capillary pressure is exceeded, water is expelled from capillary pore spaces in the caprock, which becomes permeable for the gas, which may result in gas leakage.

1.2. Recognition of structures for CO_2 storage in Poland

The topic of using geological structures for underground storage of industrial gases (carbon dioxide and hydrogen) is raising a wide interest in Poland (Tarkowski et al. 2009a; Marek et al. 2010; Dziewińska and Tarkowski 2018). Numerous anticlinal structures suitable for carbon dioxide storage have been identified and studied in the Permo-Mesozoic strata of the Polish Lowlands, in deep aquifers of the Lower and Upper Triassic, Lower Jurassic and Lower Cretaceous strata (Marek et al. 2010, 2011a, b), also using geophysical methods (Dziewińska and Tarkowski 2012, 2018). These structures are situated within a several kilometers thick series of Permo-Mesozoic rocks in the Polish Lowlands, which includes sandstone horizons of good reservoir properties. Elevated forms of these structures (anticlines, salt domes, salt pillows) are related to salt tectonics (Marek and Pajchlowa 1997). The CO_2 storage capacity of these structures has been determined (Tarkowski 2008; Uliasz-Misiak 2008; Labus et al. 2010), their ranking has been conducted (Uliasz-Misiak and Tarkowski 2010), the influence of the rock matrix on mineral sequestration of carbon dioxide (Tarkowski et al. 2011, 2015), and the use of microorganisms for monitoring carbon dioxide leakage have been studied (Tarkowski et al. 2009a). Recently, the potential use of these structures for underground hydrogen storage has also been discussed (Tarkowski 2017, 2019; Lewandowska-Śmierzchalska et al. 2018).

This paper is aimed at determining the influence of capillary pressure on the carbon dioxide storage capacity. This topic, though important, is seldom treated in publications. It is presented using the example of the CO_2 injection into the deep aquifer of the Konary structure, comparing two cases: with and without taking capillary pressure into account. This analysis belongs to the first ones in this field of research.

The simulation of the CO_2 injection into a deep aquifer in Lower Jurassic strata has been conducted by the means of a geological model built using detailed geological data on the deposit. The simulations have been conducted separately for 50 injection wells distributed all over the structure. With the injection parameters similar, this was aimed at investigating the influence of the well location on the capacity of the structure chosen for carbon dioxide storage. A gas injection was performed for the 31 years of the average hypothetical life-span of a power plant that would supply the carbon dioxide for storage. The presence of a hypothetical fault adjacent to the Konary structure resulted in the consideration of four variants (with and without the fault and taking or not taking capillary pressure at the summit of the structure into account) and also in the evaluation of their influence on the carbon dioxide storage capacity. The studies of this kind are essential for selecting the location of the carbon dioxide injection well; they provide the base for the selection of the optimum location, thus improving the economical aspect of the enterprise.

2. Geological characteristics of the Konary structure

Locations of the geological structures selected in Poland for CO_2 storage in Lower Jurassic deposits, shown against the extent of these strata is shown in Figure 1. The Konary structure is situated in central Poland. It is considered one of the best sites for underground

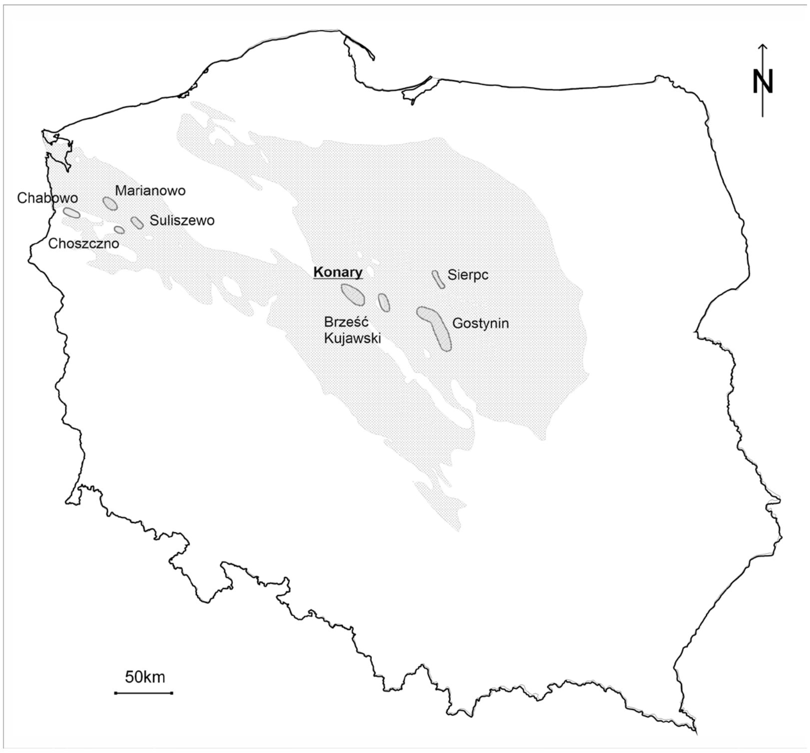

Fig. 1. Locations of the geological structures selected in Poland for CO_2 storage (based on Marek et al. 2010)

Rys. 1. Lokalizacja wytypowanych w Polsce struktur do składowania CO_2 w utworach jury dolnej carbon dioxide storage. It was ascribed to the highest index 9 (out of 10 possible) in a ranking of 36 structures in the Polish Lowlands proposed for underground storage (Uliasz-Misiak and Tarkowski 2010).

The Konary anticline (salt pillow) lies within the Kujawy Ridge, between the Góra salt dome in the north and the Izbica Kujawska dome in the south (Marek and Pajchlowa 1997; Dadlez et al. 2000). The geological sequence in this area includes a 5000–6000 m thick series of Permo-Mesozoic sedimentary rocks (Marek et al. 2010; Dziewińska and Tarkowski 2018). Several aquifers filled with brine have been identified in the Triassic, Lower Jurassic and Lower Cretaceous strata of Polish Lowlands. Two reservoir horizons in the Lower Jurassic strata, similar in their reservoir properties, have been accepted as the most favorable for CO_2 underground storage: the reservoir horizon of the Upper Toarcian Bogucice Formation and a deeper one – the reservoir horizon of the Upper Pliensbachian Komorowo Formation (discussed in the farther part of this paper) (Marek et al. 2010).

The Konary anticline has been studied by a semi-detailed reflection seismic survey and two boreholes: Konary IG-1, with the final depth of 3452.0 m, situated on the NE limb of the anticline, and a research borehole Byczyna 1, with the final depth of 5728.0 m, situated on the SE limb of the structure (Marek ed. 1974). The reservoir horizon of the Komorowo Formation has been encountered by borehole Konary IG-1 at the depth of 1077.5–1200.0 m (thickness 122.5 m) and in borehole Byczyna 1 at the depth of 1832.0–1926.0 m (thickness 94 m). The Komorowo Formation is represented by fine-, medium- and coarse-grained sandstones (in the upper part of the section); the lower part of the section features a greater proportion of argillaceous rocks. The reservoir properties of this horizon are as follows: permeability of the rocks in the reservoir horizon ~10–900 mD, porosity ~3–17%, geothermal gradient Gt = 2.9°C/100 m, deposit temperature in the reservoir horizon 35.8–48°C, pressure gradient Gc = 1040 hPa/10 m, deposit pressure 9.12–9.94 MPa. The strata of this formation are filled with chlorine-calcium brines with a mineral content of 42–49 g/dm^3. The formation is sealed at the top by Lower Toarcian clays and mudstones, with an average thickness of 125 m. A probable fault has been recognized in the southern part of the structure (Bojarski ed. 1996; Górecki et al. 2010; Marek et al. 2010).

3. Methods

3.1. Numerical geological model of the Konary structure

The numeric model of the Konary structure has been built based on geological data on the reservoir horizon of the Lower Jurassic Komorowo Formation, on the Byczyna 1 borehole log, on the structural map of the reservoir horizon under consideration and geological cross-sections (Tarkowski et al. 2011). The model boundaries were accepted so that it covers the entire structure as delineated by the –1000 m depth contour of the top of the Komorowo Formation, extending to the supposed fault in the NW periphery of the structure.

The surface area of the so defined modeled area equals approximately 92 km^2, while the surface area of the structure as delineated by the –1000 m depth contour of the Komorowo Formation is approximate 48 km^2.

Accounting for the variation in porosity and permeability of the reservoir horizon dedicated to CO_2 storage and using the data obtained from the interpretation of borehole Byczyna 1, ten different layers have been distinguished within the reservoir horizon (Table 1). In this framework, the upper part of the Komorowo Formation section is represented by sandstones with very good reservoir properties – maximum permeability of 1000 mD and maximum porosity up to 18%. On the other hand, the lower part of the section features a greater proportion of argillaceous rocks.

Table 1. Properties of the Lower Jurassic Komorowo Formation rocks in borehole Byczyna 1

Tabela 1. Właściwości skał formacji komorowskiej jury dolnej w otworze Byczyna 1

No.	Depth interval (m)	Thickness (m)	Contribution (%)	Average permeability (mD)	Average porosity (%)
1	1832–1860	28	30	900.00	16.75
2	1860–1865	5	5	330.00	16.00
3	1865–1881	16	17	725.00	16.63
4	1881–1888	7	8	63.57	9.86
5	1888–1891	3	3	101.67	10.33
6	1891–1915	24	26	435.42	14.08
7	1915–1917	2	2	90.00	9.50
8	1917–1919	2	2	300.00	10.00
9	1919–1922	3	3	10.00	3.00
10	1922–1926	4	4	195.00	9.50

For all the distinguished layers, the value of vertical permeability was accepted at 10% of the horizontal permeability value. It has been accepted that the roof and the sole strata are impermeable. Thermal properties were accepted at the same level for all the layers distinguished, namely thermal conductivity of brine-saturated rocks at 2.51 W/m°C, and specific heat at 920 J/kg°C (TE 2016).

Based on the structural map of the Komorowo Formation and using a prepared XYZ calculation sheet, a regular grid of values was constructed. Using kriging for the interpolation of the data, a set of values was determined in regular nodes of the independent variables XY and the values of their function Z. The grid so prepared (polygonal grid was used, based on a division of cells by the Voronoi method) was imported into the PetraSim TOUGH2 program. In the case discussed here, the grid cells have a surface of approximately 100 000 m^2. This grid was additionally densified near the limits of the structure to surfaces of approximately 10 000 m^2, and near the injection wells to approximate 1000 m^2. The number of cells in the PetraSim TOUGH2 program in the model so built amounted to approximately 20 000.

The boundaries of the model used for modeling in the TOUGH2 program are closed. Nevertheless, by ascribing very large volumes (about 10^{50} m^3) to the boundary cells of the grid, these boundaries may become virtually “opened” (Pruess et al. 1999). The geological model of Konary structure was built in this way. A probable fault has been recognized in the southern part of the structure, thus the geological model was created in two versions. The first assumed that the fault is absent and the boundaries of the whole model were opened. The other version assumes that the fault is present and the boundaries are closed at its location. In this case, it was accepted that the fault is completely impermeable and this may give rise to the rapid growth of pressure which may exceed the acceptable values of both fracturing pressure and capillary pressure (Lothe et al. 2014). The other properties of the model remained the same for both versions. Figure 2 presents the model of the Konary structure built using PetraSim TOUGH2 software, with marked the depth contour –1000 m of the Komorowo Formation roof, which is the structure’s boundary spill point, and with the grid denser near the boundary and also near the injection well situated at the summit of the structure.

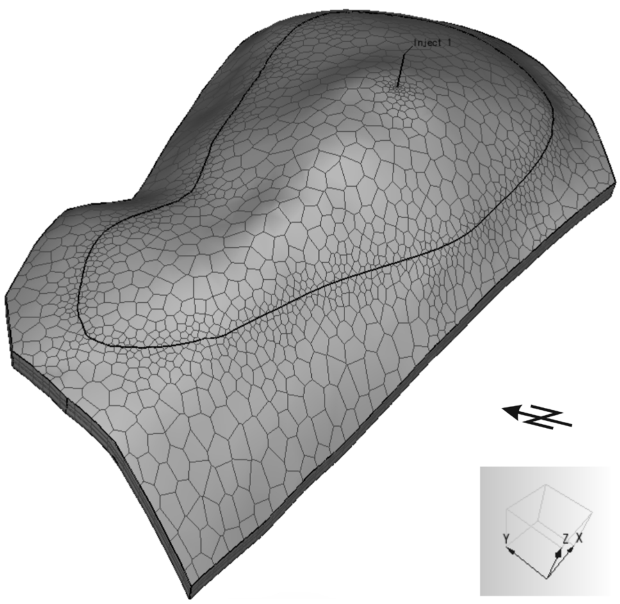

Fig. 2. Model of the Konary structure (vertical scale extended 5-fold)

Rys. 2. Model struktury Konary (5-krotne przewyższenie)

3.2. Simulation of CO_2 injection

The simulation of the CO_2 injection was performed using TOUGH2 PetraSim software with the deposit simulator of mon- and polyphase fluids, iso- and nonisothermic – TOUGH. It is widely used in deposit engineering, petroleum geology, geothermal systems and recently also successfully in carbon dioxide sequestration (Doughty and Pruess 2004). It allows for the modeling of non-isothermic and polyphase flows of mixtures of water, salt (NaCl) and CO_2 accounting for the complexity of such subsurface processes (Zhao and Cheng 2015; Yang et al. 2015). The ECO2N dedicated module allows for an analysis of polyphase flows, heat exchange and chemical reactions that take place during the CO_2 injection to a reservoir horizon. Chemical reactions represented in the ECO2N module include the stage of equilibrium between water and carbon dioxide, in liquid and gaseous phases respectively, as a function of temperature, pressure, and salinity. The range of the applicability of individual parameters of this module is adequate for most conditions encountered during CO_2 storage in deep aquifers (Pruess 2005). It also accounts for all trapping mechanisms related to CO_2 storage, except for mineral trapping (Zhang et al. 2011).

Van Genuchten's general characteristics for liquid permeability and capillary pressure and Corey's ones for relative gas permeability were used in flow modeling (Doughty and Pruess 2004). CO_2 injection modeling was performed assuming isothermal conditions. The irreducible water saturation of rocks was accepted as 0.3 (Pruess 2005; Uliasz-Misiak 2008; MŚ 2013), while rock pores compressibility as -4.5^{-10} (TE 2016).

3.3. Determination of CO_2 storage dynamic capacity

To determine the CO_2 dynamic capacity of the Konary structure, a simulation was performed of a carbon dioxide injection through one vertical well for fifty various locations. The distance from the structure's predefined boundary was greater than 1 km for all the cases studied because of the risk of injected CO_2 leakage behind the boundary. It was assumed that carbon dioxide will be injected into the entire thickness of the selected reservoir horizon. Two cases were accepted for the maximization of the CO_2 amount that can be injected into the structure. The first case assumed that the rise in pressure caused by the carbon dioxide injection into the structure will not exceed fracturing pressure calculated for each of the considered injection wells. The second case also took permissible capillary pressure in the summit part of the structure into account. These accepted guidelines resulted in four variants of conducted modeling:

- variant I assuming that no fault is present near the structure and calculation of CO_2 storage dynamic capacity does not take capillary pressure at the structure's summit into account;
- variant II assuming that an impermeable fault is adjacent to the structure and calculation of CO_2 storage dynamic capacity does not take capillary pressure at the structure's summit into account;

- variant III assuming that no fault is present near the structure and calculation of CO_2 storage dynamic capacity takes capillary pressure at the structure's summit into account;
- variant IV assuming that an impermeable fault is adjacent to the structure and calculation of CO_2 storage dynamic capacity takes capillary pressure at the structure's summit into account.

The minimum and maximum values of fracturing pressure were calculated for the ten layers distinguished in the reservoir horizon, separately for each of the 50 injection well locations. Similarly, vertical and horizontal stress for the horizon selected for CO_2 storage were calculated for each of the ten depths of the layers distinguished within the reservoir horizon. It was accepted in the calculation that $\sigma_{H,\min} = \sigma_{H,\max}$. The value of the extensional strength was accepted at 6.45 MPa (average value for typical reservoir rocks in the underground gas store Swarzów in Poland) (Woźniak and Zawisza 2011). The results of calculation of the minimum and maximum fracturing pressures and of the vertical and horizontal stresses for the well in the Konary structure in which the maximum storage capacity was obtained, with coordinates (6500; 6300), is presented in Table 2. The mean value of rock density was accepted at 2542 kg/m^3 and the gravitational constant as 9.81 m/s^2. Biot's constant α equal to 0.7 and Poisson's ratio ν of 0.25 were accepted at the level usually applied for reservoir rocks in hydrocarbon deposits. For the reasons of CO_2 storage safety, the minimum value of fracturing pressure was accepted in farther considerations, referred to as the fracturing pressure.

Table 2. Values of parameters necessary to calculate the minimum and maximum values of fracturing pressure for the Konary structure

Tabele 2. Wartości parametrów potrzebnych do obliczeń minimalnej i maksymalnej wartości ciśnienia szczelinowania dla struktury Konary

No.	Depth interval (m)	Pore pressure (reservoir) P_i (MPa)	Vertical stress σ_V (MPa)	Minimum and maximum horizontal stress $\sigma_{H,\min} = \sigma_{H,\max}$ (MPa)	The minimum value of fracturing pressure $\sigma_{f,\min}$ (MPa)	The maximum value of fracturing pressure $\sigma_{f,\max}$ (MPa)
1	944.2–972.2	10.27	23.89	12.76	17.72	21.70
2	972.2–977.2	10.45	24.31	12.98	17.95	21.96
3	977.2–993.2	10.56	24.57	13.12	18.10	22.12
4	993.2–1000.2	10.69	24.85	13.27	18.27	22.31
5	1000.2–1003.2	10.74	24.98	13.34	18.34	22.39
6	1003.2–1027.2	10.89	25.32	13.52	18.53	22.60
7	1027.2–1029.2	11.04	25.64	13.70	18.71	22.81
8	1029.2–1031.2	11.06	25.69	13.72	18.74	22.84
9	1031.2–1034.2	11.08	25.75	13.76	18.78	22.88
10	1034.2–1038.2	11.12	25.84	13.80	18.83	22.94

Special attention in variants III and IV was given to capillary pressure, which when exceeded may result in the CO_2 transferred toward the top of the reservoir formation, under the impermeable roof, by injection or by buoyancy, penetrating through capillary pores of the cap rocks. Capillary pressure may be defined by the Young-Laplace equation (Cavanagh 2010):

$$\Delta p = \frac{2\gamma \cos(\theta)}{R} \tag{1}$$

↳ Δp – capillary pressure (Pa),
γ – surface tension between CO_2 and brine (N/m),
θ – wetting angle in the system CO_2/brine/cap rock minerals (°),
R – equivalent pore space radius in caprock pore space (m).

For calculations the value of surface tension between CO_2 and brine – γ has been accepted as 22 Nm^{-1}. Tokunaga and Wan (Tokunaga and Wan 2013) accept, for typical conditions of CO_2 sequestration, (pressure of 7 to 27 MPa, temperature up to 100°C and salinity up to approximately 334 g/l) the values of this coefficient between 22 and 53 Nm^{-1}. Wang et al. (Wang et al. 2013) presented measurements of wetting angle θ on a wide spectrum of minerals in temperature 30°C and a pressure of 7 MPa (near the CO_2 critical point) and at 50°C and 20 MPa (CO_2 in the supercritical state) with various water solutions. They found that all these substrates remained hydrophilic ($\theta \leq 30°$), hence the value of the wetting angle θ in the system CO_2/brine/cap rock minerals was accepted at 30°. The equivalent pore space radius of the caprock lies in the range 0.01–0.1 μm and it was accepted based on the results obtained by Tarkowski et al. works (Tarkowski et al. 2014, 2015) for selected reservoir rocks in the Polish Lowlands. These values were used as the base for calculating the maximum acceptable capillary pressure at the top of the reservoir horizon, which equaled 7.62 MPa, while the minimum value of the acceptable capillary pressure was determined at 0.762 MPa. For the sakes of CO_2 storage safety, it was assumed that the value of acceptable capillary pressure will not exceed the minimum value so that the rise of pressure at the structure's summit caused by CO_2 injection will not exceed 0.762 MPa.

The accepted 31 year period of CO_2 injection was divided into two stages: stage I corresponding to the test injection (the first year) and stage II – the final injection (the following 30 years). The injection rate was accepted as stable for the entire 31 year period. This allowed the amount of injected CO_2 during the final injection to be increased without exceeding the acceptable pressure.

CO_2 injection to the model so built at the presented assumptions was performed for 50 different locations of the injection well. This allowed a map of the dynamic capacity of the Konary structure for all variants of the performed modeling to be drawn. This makes it possible to determine what CO_2 storage capacity can be achieved by locating a vertical injection well at a given location.

4. Results

A simulation of the CO_2 injection to the Konary structure at the accepted assumption reveals a wide range of the values of storage dynamic capacity for every variant discussed. Table 3 presents CO_2 storage dynamic capacity with injection during the first year and the next 30 years, for each of the 50 injection well locations. In the first case, the injection rate was accepted assuming that the increase in pressure caused by injection will not exceed the fracturing pressure and that gas will not leak beyond the accepted limit of the structure (variants I and II). In the second case, it was additionally assumed that the increase in pressure at the top of the structure (or at the top of the reservoir horizon in the zone adjacent to the injection well in the location discussed) will not exceed the acceptable value of capillary pressure (variants III and IV). With this assumption, the fracturing pressure value was not exceeded and no gas escape beyond the accepted limit of the structure was observed for any of the considered injection well locations.

In the case when capillary pressure was not taken into account, the maximum value of storage dynamic capacity for the model in the version without the fault (variant I) equals 49.46 million tons of CO_2, and the lowest value – 12.51 million tons of CO_2, with the mean value of 35.94 million tons of CO_2. For the model in the version with the fault (variant II), the minimum value of dynamic capacity is the same as for variant I – 12.51 million tons of CO_2, and the maximum value – 48.12 million tons of CO_2. The average value for the 50 locations of the injection well in variant II is 33.17 million tons of carbon dioxide (see Table 3).

Simulation of the CO_2 injection to the Konary structure from 50 different injection well locations resulted in the presentation of dynamic capacity maps (Figs. 3, 4), presented in the same color scale. It shows that for variant I (without fault and not accounting for capillary pressure), the lowest values were obtained when the injection well was located near the depth contour –1000 m of the roof of the Komorowo Formation which marks the limit of the structure, and at the summit of the structure. The structure's storage capacity increased radially from the summit to the contour line –900 of the roof of the Komorowo Formation, locally below this value. The greatest values were found in wells located at the outer limit of the structure, near the contour lines –800 – –900 of the roof of the Komorowo Formation, in the SW part of the structure. Meanwhile, in the N part of the structure, the greatest values were noted between the –900 m and –1000 m contours of the roof of the Komorowo Formation. The maximum value of 49.46 million tons of CO_2 was obtained by injection through a well (coordinates 8400; 3762) located on the western slope of the structure, near the contour –900 m (see Fig. 3, Table 3). After rising to the maximum value, the values of dynamic capacity for the Konary structure decrease toward the limiting contour and attained a zero value at the boundary.

For variant II (with fault, and not accounting for capillary pressure), similarly as for variant I, the lowest values were found near the outer limit of the structure and at the structure's summit. The highest values, 45–50 million tons of CO_2, were observed over a small (relative to variant I) area in the NW part of the structure, somewhat below the contour

–900 m of the Komorowo Formation roof. As for variant I, a radially spreading increase in the values of dynamic capacity was observed, with negative values present only on the N and NE slopes of the structure.

Table 3. CO_2 storage dynamic capacity for 50 locations of the injection well

Tabela 3. Pojemność dynamiczna składowania CO_2 dla 50 lokalizacji otworu zatłaczającego

Well location		CO_2 storage dynamic capacity M_{dyn} (mln tons CO_2)			
		without accounting for capillary pressure		with accounting for capillary pressure	
X	*Y*	variant I (without fault)	variant II (with fault)	variant III (without fault)	variant IV (with fault)
1	2	3	4	5	6
10 300	5 200	12.71	12.61	12.12	11.54
9 500	5 000	12.61	12.61	10.87	10.19
11 200	5 100	12.51	12.51	11.85	11.14
8 850	5 000	21.29	20.33	11.52	11.09
9 650	5 600	22.23	20.34	11.98	11.21
10 500	5 900	22.23	20.80	12.64	12.05
11 500	5 700	20.27	20.33	11.92	11.87
11 900	5 000	21.76	20.80	12.93	12.16
11 500	4 400	22.23	20.80	12.86	12.15
10 500	4 300	22.23	20.32	12.57	11.66
9 500	4 400	21.76	19.38	11.35	10.70
12 550	5 000	34.03	30.62	13.58	12.22
11 900	4 050	34.04	29.77	13.32	11.93
12 250	6 330	36.93	35.52	13.52	12.42
13 180	5 000	37.99	34.95	13.86	13.35
6 940	5 000	41.54	35.67	13.55	12.72
8 700	6 240	42.00	40.87	12.97	11.83
10 500	6 930	39.82	39.26	13.43	12.83
12 700	6 777	40.10	38.88	13.72	13.33
13 760	5 000	42.31	40.14	14.33	13.54
12 600	3 525	44.48	36.02	13.68	13.20
10 500	3 275	44.67	32.68	13.35	13.51
8 700	3 920	44.94	33.54	14.46	11.64

Table 3. cont.

Tabela 3. cd.

1	2	3	4	5	6
5 755	5 300	46.72	39.76	13.91	13.68
10 500	7 315	44.11	43.85	14.06	13.10
13 200	7 230	43.27	43.84	14.33	13.78
8 400	3 762	49.46	35.28	14.69	11.78
5 000	5 770	33.87	32.01	13.68	13.03
5 800	6 300	42.43	42.45	14.58	13.92
6 550	5 600	41.56	41.03	13.69	13.13
6 400	4 800	39.74	37.98	13.71	13.13
7 400	6 300	46.93	47.99	13.83	13.27
7 500	5 700	41.64	41.01	13.47	13.00
6 500	6 300	43.37	48.12	15.51	14.76
8 400	5 700	38.36	37.34	12.25	12.40
7 500	4 300	40.85	38.14	13.44	12.84
8 350	4 500	34.34	30.47	11.91	11.49
9 500	6 900	42.96	42.59	13.00	13.10
9 700	6 400	37.11	36.57	12.04	11.76
9 400	3 500	44.66	34.59	12.98	12.40
9 800	3 900	34.88	28.91	12.18	11.93
11 100	6 150	32.77	31.46	12.43	12.04
11 200	3 800	36.61	29.67	12.68	12.22
12 900	5 900	36.93	35.90	13.01	12.44
13 000	4 300	37.41	35.52	13.28	12.67
11 600	3 200	45.73	33.83	13.34	12.90
13 700	4 000	43.83	40.14	14.06	13.45
13 600	6 200	40.03	39.37	13.91	13.24
11 400	7 300	41.44	40.98	13.64	13.17
12 300	7 300	41.35	40.79	14.02	13.46
Min		12.51	12.51	10.86	10.19
Max		49.46	48.12	15.52	14.77
Mean		35.94	33.17	13.21	12.53

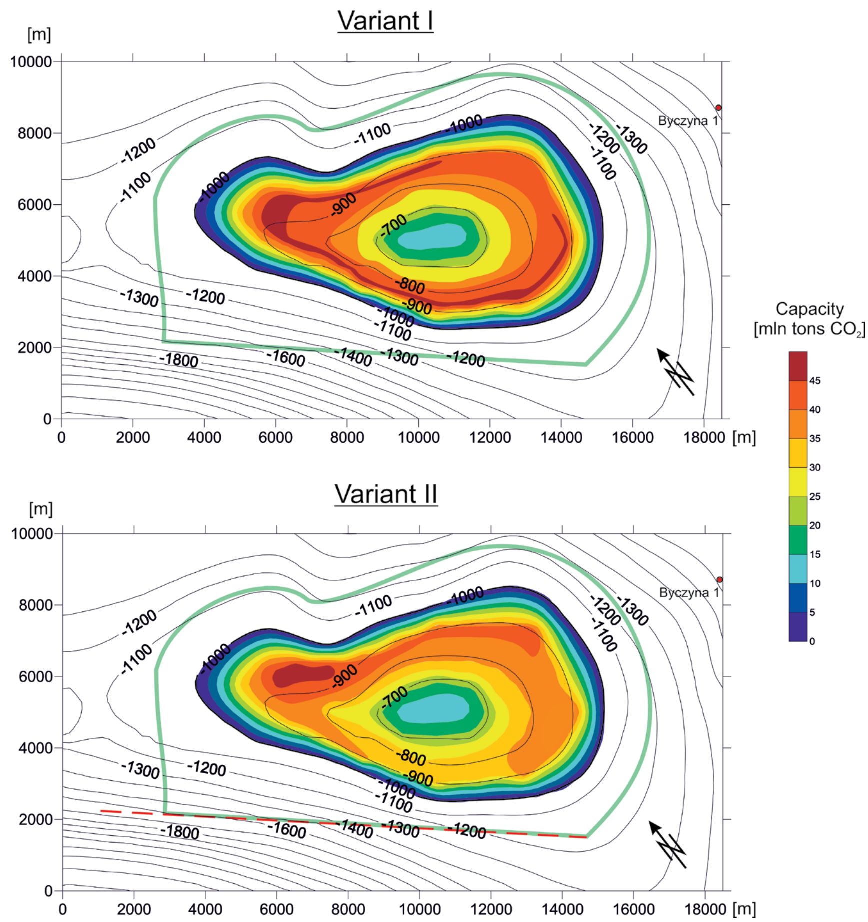

Fig. 3. Map of CO_2 storage dynamic capacity relative to locations of the injection well in the Konary structure for variants I and II

Rys. 3. Mapa pojemności dynamicznej składowania CO_2 w zależności od położenia otworu zatłaczającego w strukturze Konary dla wariantu I i II

When capillary pressure at the structure's summit was taken into account, for variant III, the minimum value of dynamic capacity obtained was 10.86 million tons of CO_2, while the maximum value was 15.52 million tons of CO_2, with the average value from 50 locations of the injection well equal to 13.21 million tons of CO_2. Lower values of average dynamic capacity were obtained in variant IV (with fault and accounting for capillary pressure), namely 12.53 million tons of CO_2, with the minimum and maximum values of 10.19 and 14.77 million tons of CO_2, respectively (see Table 3).

The map of CO_2 dynamic capacity for the Konary structure (Fig. 4) shows the lowest values for variant III with the injection well located at the summit of the structure. The increase in CO_2 storage capacity radiated from the structure's summit mainly to the –900 m

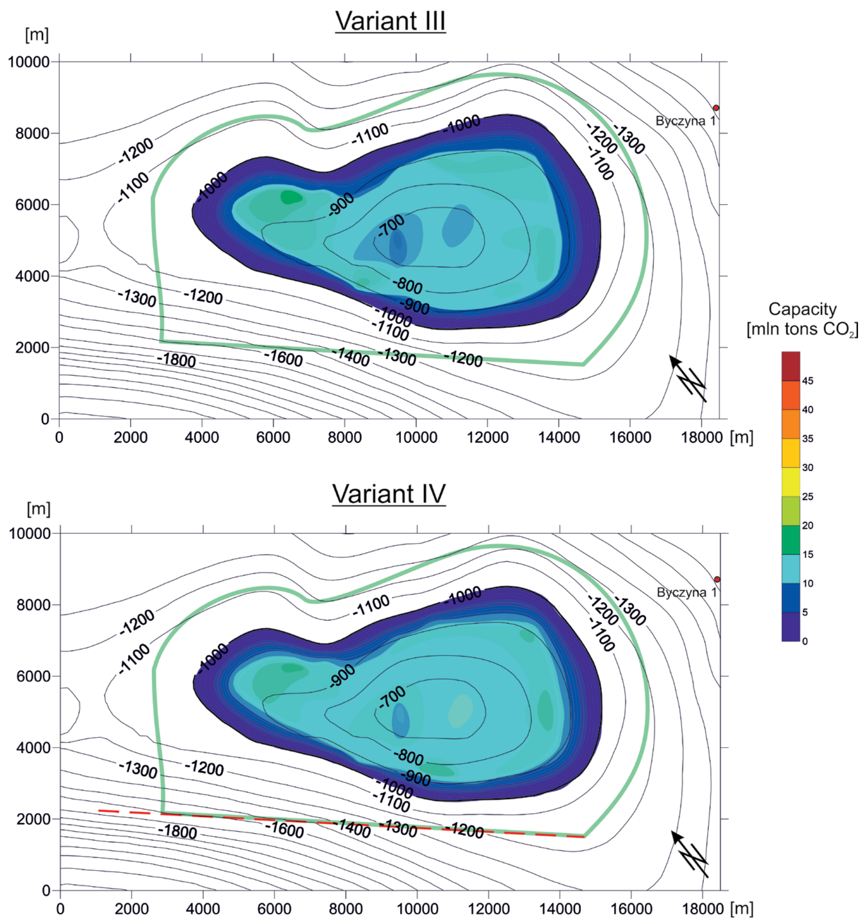

Fig. 4. Map of CO_2 storage dynamic capacity relative to locations of the injection well in the Konary structure for variants III and IV

Rys. 4. Mapa pojemności dynamicznej składowania CO_2 w zależności od położenia otworu zatłaczającego w strukturze Konary dla wariantu III i IV

contour line of the Komorowo Formation roof, and locally below it. High values of dynamic capacity were also found in boreholes located at the limit of the structure, near contours –800 to –900 m of the Komorowo Formation roof. The highest value of dynamic capacity in the NW part of the structure (up to nearly 16 million tons) was noted between contours –900 and –1000 m of the Komorowo Formation roof. It was there where the maximum value of capacity was obtained – 15.52 million tons of CO_2 (borehole with coordinates 6500; 6300). After attaining the highest values, dynamic capacity for the structure studied decreases toward the limiting contour of the structure, attaining zero value at the limit.

The lowest values for variant IV, similarly as for variant III, were found at the summit of the structure. The highest values, 14.77 million tons of CO_2, were noted over a small (relative to variant III) area in the N part of the structure, slightly below the –900 m contour of the Komorowo Formation roof, also in the well located at 6500; 6300. Similarly as for variant III radiating increase in the dynamic capacity values was observed, with elevated values only on the N and NE slopes of the structure.

A strong tendency to upward migration (toward the summit of the structure) of the injected CO_2 during injection was observed with all the 50 locations of the injection well. A good example of this phenomenon is the well on the NW slope of the structure (coordinates 6940; 5000), presented in Figure 5. It should be stressed that even though the well is located near the contour delineating the structure's boundary, the carbon dioxide plume does not cross the boundary. It rises and migrates toward the structure's summit (also after the cease of injection) by the force of buoyancy in the presence of brine. This phenomenon demonstrates that the rising carbon dioxide will increase pressure within the structure at the contact between the reservoir rock and the overlying impermeable cap rock. This implies that in the case of the Konary structure, for variants III and IV, the amount of injected CO_2 is limited mainly by the excessive increase in pressure at the summit of the structure (in some cases in the roof zone of the reservoir horizon in the direct vicinity of the injection well), whose permissible value was accepted at 0.762 MPa. For this reason, a farther injection is impossible, even though the fracturing pressure and capillary pressure in close vicinity of the well did not exceed the permissible values, and carbon dioxide did not fill the structure.

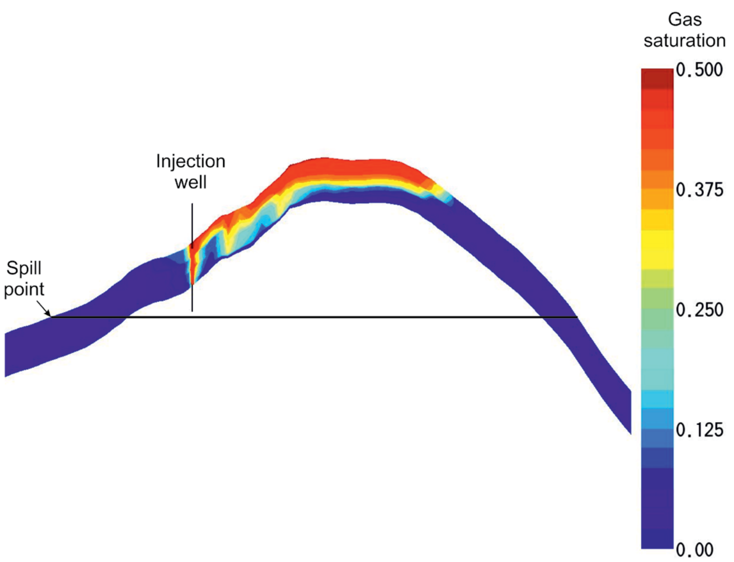

Fig. 5. NW-SE cross-section through the Konary structure showing CO_2 saturation of rocks after 31 years of injection

Rys. 5. Przekrój NW-SE przez strukturę Konary obrazujący nasycenie skał dwutlenkiem węgla po 31 latach zatłaczania

In the case of the studied structure, accounting for capillary pressure at the structure's summit resulted in lowering the dynamic capacity by 63% on average (in the version without the fault) and by 62% (version with the fault). Without accepting the fault and without considering capillary pressure (variant I) average CO_2 storage capacity equaled 35.94 million tons of CO_2, while with the presence of the fault accepted, (variant II) – 33.17 million tons of CO_2 (see Table 3). When capillary pressure was taken into account, the capacity decreased to 13.21 million tons of CO_2 on average without considering the fault (variant III) and to 12.53 million tons of CO_2 when the presence of the fault adjacent to the Konary structure was accepted (variant IV).

Similar relations are visible on the maps of CO_2 storage capacity in the Konary structure, shown in Figs. 3 and 4 drawn on the ground of simulated injection of this gas from 50 different locations of the injection well. The lowest values for every variant were observed when the injection well was situated at the summit of the structure. All variants have also shown an increase in CO_2 storage capacity radiating from the structure's summit mainly to the depth contour –900 m of the Komorowo Formation roof, locally below this contour. High values of dynamic capacity were found in boreholes located at the outer limit of the structure, near depth contours –800 to –900 m of the Komorowo Formation roof. The highest values of dynamic capacity were observed in the NW part of the structure between the contours –900 and –1000 m of the Komorowo Formation roof.

5. Discussion of results

The impact of the CO_2 injection well location, within the geological structure, on the dynamic CO_2 storage capacity in the considered structure, is a topic rarely discussed in the literature. At work Stopa et al. (Stopa et al. 2016), calculation procedures were developed and applied to optimize the location of the injection well, but this was done for another purpose - to minimize the risk of CO_2 leakage. Alternately, Okwen et al. (Okwen et al. 2014) conducted numerical simulations of CO_2 injection to evaluate the efficiency of this gas storage for various sedimentation environments at five different locations of the CO_2 injection well. This allowed the difference in this coefficient for different well locations to be noticed. And in this case, the problem was not explored, calculating only the average value of the results obtained in five locations of the CO_2 injection well. The results of the research in the presented article confirmed that the location of the CO_2 injection well within the geological structure has a significant impact on the carbon dioxide capacity for this structure.

Attempts to estimate the CO_2 dynamic capacity using injection simulation are carried out with different assumptions of pressure change in the reservoir due to the injection of carbon dioxide. One way is to assume that the pressure increase due to CO_2 injection into the structure will not exceed the fracturing pressure. For example, Agada et al. (Agada et al. 2017) conducted a simulation of CO_2 injection with twelve injection wells for the Bunter Sandstone formation in the North Sea, and the amount of CO_2 injected was set to not exceed the fracturing pressure and that the amount was within 1–10 Mt/year for a given well. A different approach to this problem was presented by Xie et al. (2016), describing the results of CO_2 injection simulation for a working demonstration CO_2 storage site in Ordos, China, assuming a constant 1.5 times hydrostatic pressure. However, the article presented by the author assumes that the increase in pressure in the structure due to CO_2 injection will not exceed the calculated fracturing pressure, as well as the increase in pressure in the structure's roof, and will not exceed the minimum capillary pressure. Similar assumptions were also adopted in many works, including Espinoza and Santamarina (Espinoza and Santamarina 2017) as well as the results of Polish national (MŚ 2013) and international (GSDG 2006) projects or larger studies on CO_2 storage (IEAGHG 2014).

Conclusions

The simulation of the CO_2 injection to the Konary structure has demonstrated how important taking capillary pressure at the structure's summit for evaluation of dynamic capacity and CO_2 storage safety into account is. Its consideration resulted in an approximately 60% decrease in dynamic capacity.

The performed simulations of CO_2 injection for 50 locations of the injection well have shown that the greatest CO_2 storage dynamic capacity may be obtained locating the injection well far away from the structure's summit, to maintain adequate distance to the predetermined structure's outer limit.

In light of the conducted CO_2 injection simulations, an increase in the number of CO_2 injection wells will not markedly contribute to the increase in carbon dioxide storage dynamic capacity.

The presence of a fault adjacent to the structure designated to CO_2 storage proved to be a factor of low importance in determining CO_2 storage dynamic capacity.

A map of CO_2 storage dynamic capacity drawn based on the results presented in this article may be a helpful tool in selecting optimum locations for the gas injection points, thus improving the economy of the enterprise.

Further research in this topic should focus on the estimation of capacity, in different locations of the injection well, in other researched and well-recognized structures suitable for CO_2 storage.

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CO_2 STORAGE CAPACITY OF A DEEP AQUIFER DEPENDING ON THE INJECTION WELL LOCATION AND CAP ROCK CAPILLARY PRESSURE

Keywords

CO_2 storage, Saline aquifer, CO_2 capacity, CO_2 storage safety

Abstract

Using the Konary anticlinal structure in central Poland as an example, a geological model has been built of the Lower Jurassic reservoir horizon, and CO_2 injection was simulated using 50 various locations of the injection well. The carbon dioxide storage dynamic capacity of the structure has been determined for the well locations considered and maps of CO_2 storage capacity were drawn, accounting and not accounting for cap rock capillary pressure. Though crucial for preserving the tightness of cap rocks, capillary pressure is not always taken into account in CO_2 injection modeling. It is an important factor in shaping the dynamic capacity and safety of carbon dioxide underground storage. When its acceptable value is exceeded, water is expelled from capillary pores of the caprock, making it permeable for gas and thus may resulting in gas leakage. Additional simulations have been performed to determine the influence of a fault adjacent to the structure on the carbon dioxide storage capacity.

The simulation of CO_2 injection into the Konary structure has shown that taking capillary pressure at the summit of the structure into account resulted in reducing the dynamic capacity by about 60%. The greatest dynamic capacity of CO_2 storage was obtained locating the injection well far away from the structure's summit. A fault adjacent to the structure did not markedly increase the CO_2 storage capacity. A constructed map of CO_2 dynamic storage capacity may be a useful tool for the optimal location of injection wells, thus contributing to the better economy of the enterprise.

POJEMNOŚĆ SKŁADOWANIA CO_2 W GŁĘBOKICH POZIOMACH WODONOŚNYCH W ZALEŻNOŚCI OD LOKALIZACJI OTWORU ZATŁACZAJĄCEGO ORAZ CIŚNIENIA KAPILARNEGO NIEPRZEPUSZCZALNEGO NADKŁADU

Słowa kluczowe

składowanie CO_2, poziomy wodonośne, pojemność CO_2, bezpieczeństwo składowania CO_2

Streszczenie

Na przykładzie antyklinalnej struktury Konary w centralnej Polsce zbudowano model geologiczny dolnojurajskiego poziomu zbiornikowego oraz przeprowadzono symulację zatłaczania CO_2 50 różnymi lokalizacjami otworu zatłaczającego. Wyznaczono pojemność dynamiczną składowania dwutlenku węgla struktury dla rozpatrywanych otworów oraz opracowano mapy pojemności składowania CO_2 bez uwzględniania oraz przy uwzględnieniu ciśnienia kapilarnego. Chociaż odgrywa istotną rolę w utrzymaniu szczelności nadkładu, ciśnienie kapilarne nie zawsze jest uwzględniane w modelowaniu zatłaczania CO_2. Jest istotnym czynnikiem wpływającym na pojemność dynamiczną oraz bezpieczeństwo podziemnego składowania dwutlenku węgla. Przekroczenie jego dopuszczalnej wartości powoduje wyparcie wody z kapilar nadkładu, który staje się przepuszczalny dla gazu, co w konsekwencji może prowadzić do wycieku gazu. Wykonano dodatkowe symulacje w celu określenia, w jakim stopniu uskok w pobliżu struktury wpływa na pojemność dynamiczną dwutlenku węgla.

Wyniki symulacji zatłaczania CO_2 do struktury Konary pokazały, że uwzględnienie ciśnienia kapilarnego w szczycie struktury wpłynęło na obniżenie pojemności dynamicznej o około 60%. Największą pojemność dynamiczną składowania CO_2 otrzymano, lokując otwór z dala od szczytu struktury. Obecność uskoku w sąsiedztwie struktury nie przyczyniła się znacząco do zmiany pojemności dynamicznej składowania dwutlenku węgla w tej strukturze. Mapa pojemności dynamicznej składowania CO_2 może być pomocnym narzędziem do wyboru optymalnych miejsc do zatłaczania tego gazu, przyczyniając się do podniesienia ekonomiki przedsięwzięcia.