GOSPODARKA SUROWCAMI MINERALNYMI

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A concept of Enhanced Methane Recovery by high pressure CO_2 storage in abandoned coal mine

Introduction

Energy production from fossil fuels causes significant CO_2 emissions into atmosphere. Along with growing demand for energy CO_2 emissions will increase with implications for global climate. Taking into consideration current level of world economy growth and policies the world's primary energy needs are projected to grow by 55% between 2005 and 2030. Thus, it is estimated that carbon emissions within the next 30 years will almost double (World Energy Outlook 2007).

European Union member states pledged to reduce their CO_2 emissions in average by 8% by the year 2012 which due to lack of perspectives for conventional energy sources might be difficult to implement. Thus, there is a need to develop new technologies of Carbon Capture and Storage (CCS).

Among many considered options such as ocean storage or mineral trapping, geological sequestration is the most developed one and includes storage in (Geological… 2004):

- deep saline aquifers,
- unmineable coal seams,
- depleted gas/oil reservoirs,
- mine caverns,
- underground mines.

Specific sites selected for CO_2 storage in Poland were identified and analyzed in the following publications (Uliasz-Misiak 2007; Tarkowski, Uliasz-Misiak 2005). One of the

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concepts which was not thoroughly investigated is storing CO_2 under high pressure in abandoned coal mines. However, underground coal mines may be an interesting option for CO_2 storage due to its abundance, usually close location to emission sources and relatively high storage capacity. Due to existing surface infrastructure and known underground void distribution costs of coal mine conversion into CO_2 sink might be comparatively lower than in case of other reservoirs. It might be also an alternative for conventional methods of mine closure. This concept might have additional advantage of enhanced coalbed methane recovery from remaining coal seams.

On the other hand, storage safety of trapped gas in abandoned mine is the main issue. Gas may leak through faults, cracks and fissures formed by former mining operation.

Literature survey reveals that mines converted into high pressure reservoirs should have the following features:

- gas tight structure capable of withstanding long term high pressure of gas,
- high storage capacity which comprises of mine voids and remaining coal seams with CO_2 sorption capacity,
- remaining coal-seams with high methane content,
- low storage costs.

Fulfilling of all the abovementioned requirements will ensure safe CO_2 storage for many years.

Gas in a coal mine can be stored in three modes:

- as a “free gas” in mine voids or porous rock mass structures,
- as an adsorbed gas in remaining coal seams,
- as a gas dissolved in mine water (brines).

Literature survey reveals that storage capacity of an underground coal mine is considerably increased by CO_2 adsorbed on remaining coal seams (Cisek et al. 2001; Moerman 1984). It is estimated that CO_2 adsorbed on coal may accounts for up to 80% of the total storage capacity.

The objective of the study is to asses the storage capacity of an abandoned coal mine converted into CO_2 storage site with focus on CO_2 adsorption on coal. Additionally, simulation study of coalbed methane recovery enhanced by CO_2 stored in a mine was done. For the purpose of a study one of the active Polish coal mines located in Upper Silesian Coal Basin was selected and its storage capacity has been estimated based upon analysis of mine data and coal sorption experiments.

Methane recovery simulations were run for a hypothetical seam with methane content typical for southern part of Upper Silesian Coal Basin at the depth of 1000 m.

1. High pressure gas storage in abandoned coal mine

The main difference between temporary gas reservoir in underground coal mine and a CO_2 sequestration project is that in temporary gas reservoir infiltration water may be pumped through the time of storage operation. If we consider CO_2 sequestration in abandoned coal mine that option is economically (cost of water pumping) and technically unjustified because of the fact that the purpose of CO_2 sequestration projects is to store the gas for hundreds or even thousands years.

Piessens & Dussar proposed concept (Piessens & Dussar 2000), which considers storing CO_2 under the pressure that equals or exceeds hydrostatic pressure in the mine and prevents the influx of water. Theory assumes that at initial conditions free space is filled with CO_2 and mine is dry. The pressure of CO_2 at the initial conditions is equal or slightly higher than specific gravity of gas multiplied by the depth of mine. Because of the difference between density of CO_2 and water the pressure at the bottom of the reservoir will be lower than the hydrostatic in host rock. As a result, water will enter the reservoir. Rise of mine water will compress CO_2 and pressure build-up will occur at the top seal of reservoir. Finally, reservoir pressure higher than hydrostatic will be reached at the top seal. CO_2 might also migrate out of the reservoir into host rocks. This flux is neglected however, as its importance in non-permeable host rock is difficult to estimate and instead worst-case scenario (maximum pressure build-up at the top seal) is considered. The influx of formation water will continue until the pressure at each level of the reservoir filled with CO_2 is higher than hydrostatic pressure. The maximum pressure condition is not an equilibrium condition since the reservoir pressure is higher than the hydrostatic pressure in the host rock. Therefore, CO_2 will escape from the reservoir and migrate laterally into the host formation. This will result in a near complete flooding of the mine but does not violate the terms for CO_2 sequestration as the gas will be trapped by the top seal.

As it was mentioned before, CO_2 in the mine will be stored as a free gas in mine voids, in solution in the mine water and adsorbed on coal. The volume of voids can be easily estimated based on mine data i.e., width, height and length of mine galleries, roadways, longwalls and porosity of gob area. The amount of CO_2, which will dissolve in water is a function of pressure, temperature and chemical composition (mainly salinity or total dissolved solids). The amount of CO_2 adsorbed on coal can be estimated knowing the remaining reserves of coal and its sorption capacity. In order to estimate sorption capacity of coal laboratory experiments must be conducted.

Total CO_2 storage capacity of a coal mine at the maximum pressure condition will be the sum of:

$$M_{CO_2} = M_v + M_w + M_{ads} + M_a \tag{1}$$

where:

M_{CO_2} – total mass of CO_2 stored in a mine [t],
M_v – mass of CO_2 stored in mine voids as a free gas [t],
M_w – mass of CO_2 dissolved in water [t],
M_{ads} – mass of CO_2 adsorbed on remaining proven reserves [t],
M_a – mass of CO_2 adsorbed on additional reserves (ascertained potential) [t].

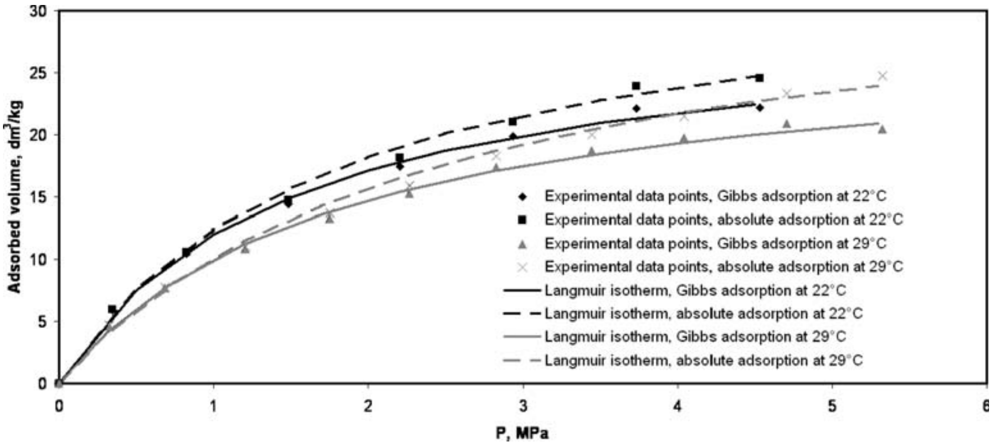

Fig. 1. Experimental results of CO_2 adsorption on coal and fitted Langmuir isotherms

Rys. 1. Eksperymentalne wyniki adsorpcji CO_2 na węglu oraz model izotermy Langmuira

In order to calculate the first two parts of the equation i.e., mass of CO_2 stored in mine voids and dissolved in water the vertical reservoir simulator CO_2-VR was used. The mass of CO_2 adsorbed on remaining proven reserves and additional reserves was calculated on the basis of mine data and sorption laboratory experiments (Fig. 1).

The vertical reservoir simulator CO_2-VR uses the abovementioned assumption of high pressure CO_2 storage in an abandoned coal mine. Mine, which was used for a case study currently has two extraction levels: 500 m and 650 m where volume of voids can be determined upon the length and cross-section of workings. In future, it is planned to access deeper seams located at 750 m and 850 m depth. The volume of future voids can be roughly estimated knowing the amount of developed reserves and extraction ratios. Current volume of mine voids i.e., workings was decreased by the consolidation factor of 0.5, gob area was assumed to have consolidation factors of 0.17, 0.13, 0.10 and 0.007 at the depths of 500 m, 650 m, 750 m and 850 m respectively and was calculated using the equation (2).

$$V_g = R_e \cdot (\rho \cdot h)^{-1} \cdot h \cdot n \qquad (2)$$

where:

V_g – void volume in gob area [m^3],
R_e – mineable reserves [t],
h – average seam thickness [m],
ρ – coal density [t/m^3],
n – gob consolidation factor as a function of depth.

One of the most important parameter in the CO_2-VR programme is a maximum allowable pressure at the top seal given as a percentage of hydrostatic pressure. It was assumed that shafts are sealed up to the depth of 440 m and the CO_2 pressure cannot exceed 30% of the hydrostatic pressure at that depth i.e., 5.85 MPa.

Results of calculation showed that the total storage capacity of a mine (without adsorption potential) is $3.5 \cdot 10^6$ t of CO_2 under pressure of 5.43 MPa. Average density of CO_2 in a mine is 312 kg/m^3. The calculation results are done for the pressure equilibrium condition, which is defined as the state of reservoir at which the pressure at the contact of mine water and CO_2-fluid is equal to the hydrostatic pressure in the host rock. This means that the pressure in the reservoir filled only with CO_2 are higher or equal to the hydrostatic pressure.

The mine will be flooded up to the depth of approximately 620 m, above that level CO_2 will be compressed. Below the depth of 620 m CO_2 will be dissolved in mine water. Thus, the volume of voids accessible for "free" gas will be 48% of the total void volume i.e., 8.3 mln m^3. The calculated amount of gas that could be stored in a mine is only the amount of gas stored in voids and dissolved in water, not adsorbed on coal. In order to estimate the amount of CO_2 that could be adsorbed on remaining coal a simple approach based on the difference between the developed reserves and mineable reserves (i.e., mine losses) was used. For the purpose of the study equation (3) used to calculate the amount of CO_2 adsorbed on coal was developed:

$$M_{ads} = \left[m_1 - \left(\frac{(a+m)}{100} \cdot m_1 \right) \right] \cdot \left[\frac{V_L \cdot P}{P_L + P} \right] \cdot \rho_{CO_2} \tag{3}$$

where:

M_{ads} – amount of CO_2 adsorbed on coal [t],

m_1 – mine losses [t],

$m_1 = (R_d - R_d \cdot k)$,

R_d – developed reserves [t],

k – extraction ratio,

a – average ash content of coal [%],

m – average moisture content of coal [%],

P – pressure of CO_2 in reservoir at certain depth [MPa],

V_L – Langmuir volume (absolute adsorption) [m^3/t],

P_L – Langmuir pressure (absolute adsorption) [MPa],

ρ_{CO_2} – CO_2 density at normal conditions ($1.977 \cdot 10^{-3}$ t/m^3).

Langmuir constants determined in laboratory as well as consolidation factors, mine developed reserves and recovery ratios based on accessible data from the mine company were used in calculation. Summary of data used in calculation are presented in Table 1.

The total amount of CO_2 adsorbed on remaining coal was calculated to be $3.53 \cdot 10$ t. Because of the fact that in calculation always "worst case" scenario was taken into account

TABLE 1

Summary of data used in calculation of adsorbed CO_2 on remaining coal

TABELA 1

Podsumowanie danych użytych w obliczeniach CO_2 zaadsorbowanego na resztkach pokładów węgla

Level (depth)	R_d [th. t]	k [–]	m [%]	a [%]	V_L [m³/t]	P_L [MPa]	P^* [MPa]
500	44 619	0.58	11.5	11	34.6	1.8	5.6
650	76 327	0.60					6.1
750	93 569	0.62			35.3	2.5	6.5
850	6 349	0.65					6.7

and the fact that there is a huge possibility of connections to remaining proven reserves this amount has been increased by 30% (ascertained potential). The extraction factor for proven reserves was estimated to be 0.33, which means that over 70% of coal remains in the deposit. In the Figure 2 the amount of CO_2 adsorbed on mine losses increased with additional 30% is presented.

Finally, the total amount of CO_2 that could be sequestered in a mine, which is the sum of all four components of the equation 1 was calculated to be $8.09 \cdot 10^6$ t.

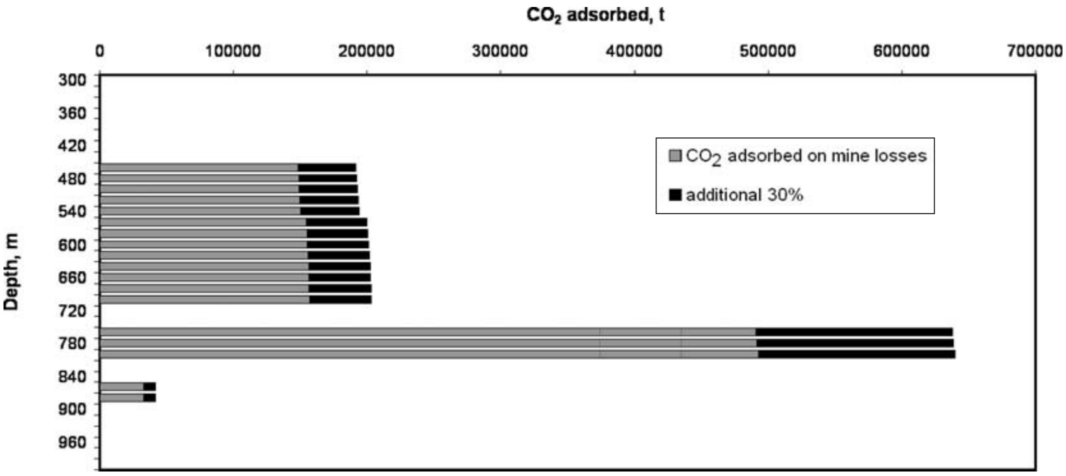

Fig. 2. The amount of CO_2 adsorbed on mine losses of a case study mine with additional 30% of ascertained potential

Rys. 2. Ilość CO_2 zaadsorbowana na pozostałych pokładach węglowych przykładowej kopalni powiększona o 30%

2. Methane recovery from coal mine converted into CO_2 reservoir

Coalbeds usually have high gas content (mostly methane). In Poland, Upper Silesian Coal Basin (USCB) has the biggest coalbed methane potential among other Polish basins, estimated total reserves have about 254 billion m^3 and economically viable to produce approximately 150 billion m^3 (Kwarciński et al. 2006). Currently, methane extraction is conducted in 18 mines where 180-200 million m^3 is captured yearly.

Taking into consideration methane content in USCB and the fact that CO_2 is used for enhancing methane recovery, estimation of influence of injected CO_2 into abandoned coal mine seems to be reasonable. So far, four field experiments of enhanced coalbed methane (ECBM) recovery were performed i.e.: RECOPOL project in Poland (Kaniów), Coal-seq in USA (San Juan Basin, border of CO and NM states), Fenn-Big Valley (Alberta, Canada) and in Japan (Hokkaido).

For the purpose of the study COMET3 Advanced Resources' COMET3 finite difference reservoir simulator for coalbed methane (CBM) and gas shale reservoirs were used. Advanced technical features of simulator include dual-permeability option for coalbed methane (CBM) reservoirs and multi-component (CH_4, CO_2 and N_2) sorption for enhanced coalbed methane (ECBM) recovery and carbon sequestration (CO_2 sequestration) applications.

In order to simulate gas and water production from coalbeds dual porosity model is used. The model is based on the idealization of fractured media by Warren and Root (Warren, Root 1964). Flow of gas and water occurs in cleats or fractures (also called secondary porosity system) and is governed by Darcy flow. The cleat system is assumed to be continuous and provides flow paths to producing wells. Gas is stored in primary porosity system (coal matrix) and flows via diffusion from discontinuous matrix blocks into the fracture system.

The main differences between the methane recovery from virgin coalseams and simulated problem are:

1. **Access to the seam from the mine side** (longwall panel) – pressure at that side is approximately an atmospheric pressure,
2. **Increased permeability of the coalseam** due to former mining operation in the part adjacent to longwall panel,
3. **CO_2 is adsorbed through the whole surface of the face** – much higher adsorption (injection) space than a classic well drilled from the surface.

To simulate the abovementioned conditions the following assumptions were done (Fig. 3):

1. Constant pressure boundary (thin row of gridblocks) with pressure set to atmospheric was designed. The dimensions of constant pressure boundary are 5.8 · 50 m. Average width of longwall in Poland is 200 m and because of that fact the length was set to be 50 m (1/4 of 200 m).
2. Permeability in constant pressure boundary was set to be 20 md (10 times higher than in the rest of the seam).
3. Three injection wells (inj1, inj2, inj3) were placed in constant pressure boundary and simulate injection of a CO_2 from a longwall panel.

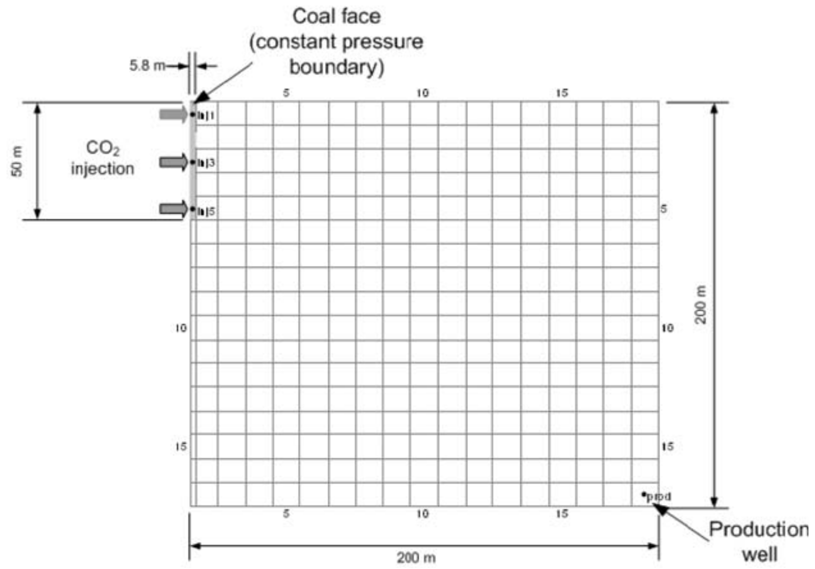

Fig. 3. Gridblocks designed for simulation study

Rys. 3. Siatka obliczeniowa użyta w symulacjach

TABLE 2

Input data used in simulations

TABELA 2

Dane wejściowe użyte w symulacjach

Parameter, unit	Value
Seam thickness, m	1.5
Depth, m	1000
Permeability (x, y, z), md	2, 2, 2
Porosity, %	1
Sorption time (CH_4, CO_2), days	10, 15
Reservoir pressure, MPa	10.02
Water saturation, %	100
Temperature, °C	33
VL*, m^3/t	8.7
PL, MPa	3.7
Coal matrix shrinkage, MPa^{-1}	$1.38 \cdot 10^{-6}$
Pore volume compressibiliy, MPa^{-1}	$1.38 \cdot 10^{-8}$
CO_2 differential swelling factor, –	1
Bottomhole pressure of production well, MPa	0.3
Bottomhole pressure of injection wells, MPa	10.4

* Value decreased by ash and moisture content = 20%.

Simulations were done for the quarter of 0.16 km^2 symmetric element. Results of simulation are shown for the whole 0.16 km^2 area. Input data for the simulations are typical values for high methane content coal seams in Upper Silesian Coal Basin and were taken from the following publications (Reeves, Taillefert 2002, McCants et al. 2001) and also obtained in laboratory experiments of CO_2 and CH_4 sorption on coal, see Table 2.

Access to the coal seam through coal face causes reservoir pressure decrease, gas desorption and dewatering. Thus, it was assumed that the gap between the mine closure and conversion into gas reservoir lasts two years and after that time methane is extracted and CO_2 injected.

Flow bottomhole pressure of injection wells was set as 10.3 MPa and is 0.3 MPa higher than reservoir pressure.

Coalbed methane production depends on many factors like: reservoir pressure, water saturation, permeability and gas content. Due to lack of precise data concerning gas saturation of USCB 60% and 80% maximum gas saturation measured in laboratory were assumed. Coal seams in USCB have low permeability varying slightly between 1.5–2.0 md. Thus, permeability value was set as constant 2 md.

In the course of a study, it was observed that fracturing of wells have a significant impact on methane recovery in the first years of production period. Thus, it was assumed that production well is fractured and skin factor for production well of –3 was set.

For both the cases (i.e. 80% and 60% methane saturation) the influence of CO_2 injection was assessed. The CO_2 injection and methane production starts after 2 years (time gap between the coal production abandonment and filling the mine with CO_2) and was simulated for 18 years.

The results of simulation were presented in Fig. 4 for 80% of saturation and in Fig. 5 for 60% of saturation.

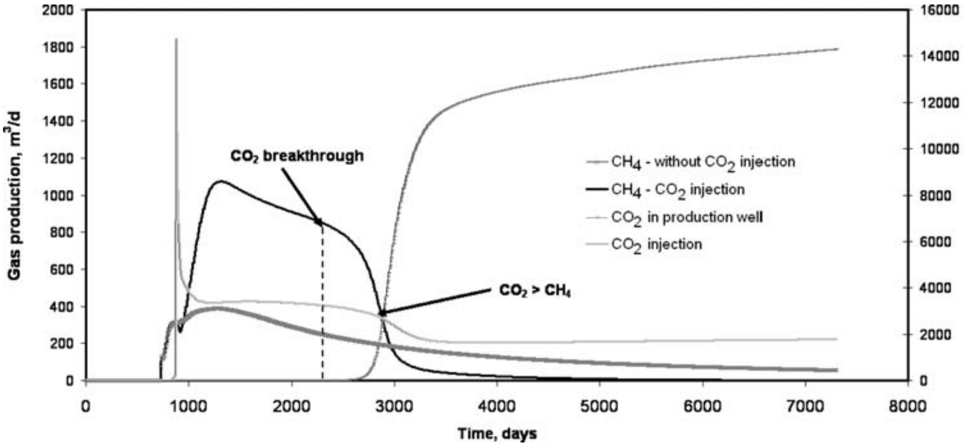

Fig. 4. Comparison of gas production rate with and without CO_2 injection for 80% methane saturation

Rys. 4. Porównanie uzysku gazu bez/ze stymulacją zatłaczaniem CO_2
do pokładu dla 80% nasycenia pokładu metanem

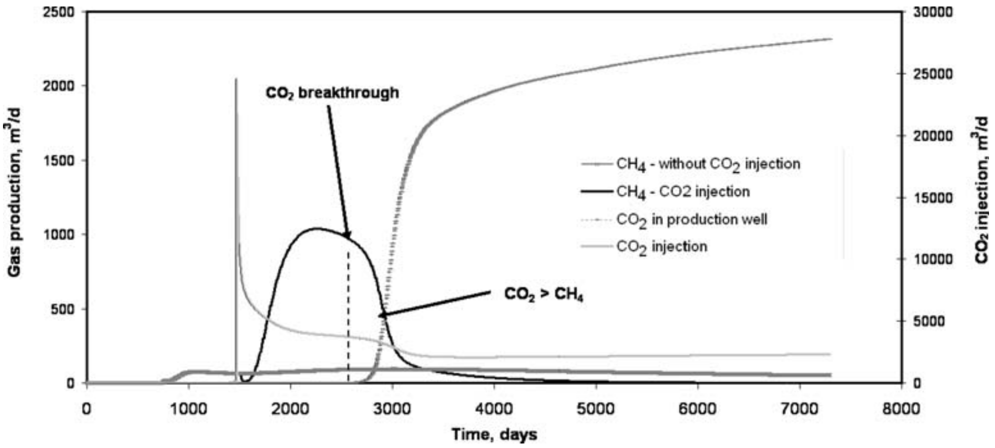

Fig. 5. Comparison of gas production rate with and without CO_2 injection for 60% methane saturation

Rys. 5. Porównanie uzysku gazu bez/ze stymulacją zatłaczaniem CO_2
do pokładu dla 60% nasycenia pokładu metanem

In comparison to base case where with no CO_2 injection methane production rates increases 3 to 4 times in the initial stage of production (first 3–4 years). In case of 60% methane saturation CO_2 breakthrough is observed after approximately 5.3 years whereas in case of 80% methane saturation after appr. 4.8 years.

Conclusions

One of the places where CO_2 can be stored are abandoned coal mines which exist in abundance especially in Europe. Mines selected for CO_2 storage must have specific features which allow safe storage of gas. Although the total storage capacity is not significant in comparison to other geological storage sites close location to emission sources and possibility of enhanced methane recovery are the biggest advantage of this concept. Computer analysis showed that CO_2 injection considerably increases methane production rates in the first three years of production both for 60% and 80% methane saturation. Thus, methane recovery may offset some of the investment costs related to conversion of coal mine into underground CO_2 sink.

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KONCEPCJA INTENSYFIKACJI WYDOBYCIA METANU POPRZEZ WYSOKOCIŚNIENIOWE SKŁADOWANIE CO_2 W ZLIKWIDOWANEJ KOPALNI

Słowa kluczowe

Dwutlenek węgla, zlikwidowana kopalnia węgla, składowanie CO_2, sorpcja gazu, intensyfikacja wydobycia metanu

Streszczenie

Wobec zwiększającej się emisji dwutlenku węgla zmierza się do redukcji emisji tego gazu ze źródeł stacjonarnych. Przy założeniu odpowiednich warunków geologicznych takich jak: szczelność nadkładu i duża objętość pustek poeksploatacyjnych jednym z miejsc podziemnego (geologicznego) składowania CO_2 mogą być zlikwidowane kopalnie węgla kamiennego. W artykule przedstawiono koncepcję wysokociśnieniowego składowania CO_2 w zlikwidowanej kopalni węgla kamiennego jako jedną z metod składowania tego gazu. Dwutlenek węgla może być składowany w kopalni jako gaz wolny, gaz rozpuszczony oraz jako gaz zaadsorbowany w pozostałych pokładach węglowych. Oszacowano pojemność przykładowej kopalni węgla kamiennego jako wysokociśnieniowego składowiska CO_2 na podstawie danych z kopalni oraz pomiarów sorpcji tego gazu na węglu. Całkowita ilość CO_2 jaki mógłby zostać zmagazynowany w kopalni wynosi około $8{,}09 \cdot 10^6$ t. Przeanalizowano również możliwość stymulacji odzysku metanu z pozostałych resztek pokładów węglowych, jaka może zaistnieć po zatłoczeniu CO_2 pod ciśnieniem do kopalni. W tym celu użyto symulatora złożowego złóż niekonwencjonalnych i danych charakterystycznych dla Górnośląskiego Zagłębia Węglowego. Symulacje wykazały znaczny wpływ zatłaczania CO_2 do kopalni na uzysk metanu w otworach wierconych z powierzchni i ponad dwukrotne zwiększenie wydobycia tego gazu w początkowym okresie eksploatacji.

A CONCEPT OF ENHANCED METHANE RECOVERY BY HIGH PRESSURE CO_2 STORAGE IN ABANDONED COAL MINE

Key words

Carbon dioxide, abandoned coal mine, CO_2 storage, gas sorption, Enhanced Methane Recovery

Abstract

Due to increasing carbon dioxide emissions new methods of carbon capture and storage away from biosphere are being under investigation. Considering favorable geological structure i.e.: impermeable overburden and large volume of mine voids one of the places of geological CO_2 storage can be abandoned underground coal mines. The article presents the concept of CO_2 high pressure storage in abandoned coal mine as one of the methods of its geological sequestration. CO_2 can be stored in a mine as a free gas, gas dissolved in water and gas adsorbed in remaining coal seams. Estimation of storage capacity of a mine was done with the use of data from the mine as well as laboratory sorption experiments. Estimated storage capacity of a case study mine as a high pressure CO_2 sink was $8.09 \cdot 10^6$ t. Enhanced methane recovery from remaining coal seams which may occur after CO_2 injection was also analyzed. For the purpose of the study reservoir simulator for unconventional reservoirs was used. Input data were typical for Upper Silesian Coal Basin. Results of the study indicate that injection of CO_2 into a mine enhance methane recovery through surface wells.