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# Research on the Processes of Injecting $CO_2$ into Coal Seams with $CH_4$ Recovery Using Horizontal Wells

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**Abstract:** The paper presents a research study on modeling and computer simulation of injecting $CO_2$ into the coal seams of the Upper Silesian Coal Basin, Poland connected with enhanced coal bed methane (ECBM) recovery. In the initial stage of the research activities, a structural parameter model was developed specifically with reference to the coal-bearing formations of the Upper Carboniferous for which basic parameters of coal quality and the distribution of methane content were estimated. In addition, a lithological model of the overall reservoir structure was developed and the reservoir parameters of the storage site were analyzed. In the next stage of the research, the static model was supplemented with detailed reservoir parameters as well as the thermodynamic properties of fluids and complex gases. The paper discusses a series of simulations of an enhanced coalbed methane recovery process with a simultaneous injection of carbon dioxide. The analyses were performed using the ECLIPSE software designed for simulating coal seam processes. The results of the simulations demonstrated that the total volume of $CO_2$ injected to a designated seam in a coal mine during the period of one year equaled 1,954,213 $sm^3$. The total amount of water obtained from the production wells during the whole period of the simulations (6.5 years) was 9867 $sm^3$. At the same time, 15,558,906 $sm^3$ of gas was recovered, out of which 14,445,424 $sm^3$ was methane. The remaining 7% of the extracted gas was carbon dioxide as a result of reverse production of the previously injected $CO_2$. However, taking into consideration the phenomena of coal matrix shrinking and swelling, the total amount of injected $CO_2$ decreased to approximately 625,000 $sm^3$.

**Keywords:** CCS; $CO_2$ sequestration; clean coal technologies; methane recovery; coalbed methane recovery

## 1. Introduction

Currently, $CO_2$ sequestration in deep unmineable coal seams with parallel methane recovery is considered as one of the potential methods of carbon dioxide utilization [1,2]. In the enhanced coal bed methane (ECBM) technology, the injected $CO_2$ displaces methane on account of the preferential adsorption of $CO_2$ in coal. In general terms, the technology consists in the desorption, diffusion and filtration of the methane adsorbed within the coal matrix towards the production wells at the same time when $CO_2$, which is subject to the same processes, will follow the reversed path, i.e., the desorption, diffusion and filtration in coal [3–6]. During the ECBM process, the permeability in the vicinity of the injection well gradually decreases, whereas in the vicinity of the production well it first increases and then decreases. This phenomenon is connected with the process of permeability changes within the ECBM technology [7]. The transformation of pore and cleat structures of coal connected with the supercritical $CO_2$ leads to the increase in permeability within the zone of coal strata, which constitutes a key factor for $CO_2$ sequestration and the efficiency of $CH_4$ production [8–10]. Lowering the pressure of fluids in the production well and the removal of coal seam waters, which initiates the process of methane desorption accelerated by injecting $CO_2$ to the coal seam through the injection well, constitute the point of departure. The phenomenon of displacing methane by $CO_2$ is based on the assumption that carbon dioxide under the pressure of about 7.38 MPa (i.e., below the critical point) characterizes of greater molecule affinity in relation to coals than methane does (the most frequently quoted preferential sorption ratio is 2:1). In the next stage of the process, the desorbed methane undergoes diffusion through the coal matrix towards the cleat system where it is filtered, according to a pressure gradient, towards the production wells [11]. The ECBM technology is still in the research phase, and, consequently there remain numerous aspects that have not been fully recognized yet, for example the scope of preferential sorption of $CO_2$ in relation to $CH_4$, the flow of the process once the critical point has been achieved as well as the impact of coal physical properties [12–18]. ECBM constitutes a method, which combines $CO_2$ sequestration in coal seams with the recovery of coal bed methane, which can achieve 72% efficiency [12]. ECBM projects using $CO_2$ and $N_2$ have been carried on since the 1990s in San Juan Basin (USA). Such experimental ECBM works showed that the injection of these gases is technically and economically feasible because it resulted in an increase in methane extraction by about 17–18% in the case of $CO_2$ injection and about 10–20% in the case of $N_2$ injection [19–21].

Carbon dioxide stored in porous geological formations is perceived almost exclusively as waste in light of Polish legislation and current technological development. Within the framework of Polish legislation, the concept of waste was set out in the Act of 14 December 2012 On Waste (consolidated text of 15 March 2019 Journal of Laws of 2019, item 701) [22]. The Act on Waste precisely lays down the measures aiming at the protection of the natural environment and human health by means of preventing or mitigating the adverse impacts of the generation and management of waste. The legislator defined waste as any substance or object, which the holder discards, or intends, or is required to discard. However, the legislator singled out a few exceptions, in the case of which the provisions of the act do not apply. Carbon dioxide designated for underground storage in order to execute a CCS demonstration project constitutes such an exception as stipulated by the Geological and Mining Law Act of 9 June 2011, article 1, item 3 (consolidated text of 4 April 2019, Journal of Laws of 2019, item 868) [22].

Considering the conditions of Polish coal resources, the ECBM technology could be applied in the Upper Silesian Coal Basin (USCB) [23]. It is worth mentioning that a few years ago, a unique pilot project RECOPOL (Reduction of $CO_2$ emission by means of $CO_2$ storage in coal seams in the Silesian Coal Basin of Poland) utilizing the ECBM technology was executed in the aforementioned coal basin. The experimental site of RECOPOL, which was one of the first projects of such a kind in the world, was located in a region encompassing the coal seams belonging to Silesia coal mine [24,25].

In contrast to the generally accepted criteria for the selection of formations designated for $CO_2$ sequestration in saline aquifers [26,27], the criteria regarding the selection of sites suitable for the application of ECBM technology have in large part a different character. The assumptions that are of a more general nature constitute an exception. The general criteria include a favorable depth interval within the range of 800–2500 m, the minimum depth of approximately 800 m because of the so called $CO_2$ critical point connected with the temperature and pressure of the rock mass as well as safety conditions related to the occurrence of impermeable rock formations and weak tectonic engagement of the rock mass. Apart from the above mentioned general assumptions, parameters that are directly connected with the specific coal seams, namely the methane content, the petro-physical parameters and, especially permeability are of fundamental importance for the selection of potential $CO_2$ storage sites.

One of the most significant issues concerning the $CO_2$ storage in coal seams is to protect the existing resources as well as to ensure that they are accessible for mining activities. Basically, the seams that are $CO_2$ saturated as a result of carbon dioxide sequestration should be regarded as lost in terms of underground exploitation. The selection of potential sites designated for $CO_2$ sequestration is determined by restrictions related to environmental protection, and, especially to land and urban development. Limited areal distribution of the coal seams within the Upper Silesian Coal Basin considerably decreases the potential of selecting $CO_2$ storage sites. In light of the above mentioned conditions, the following assumptions have been adopted for the selection of carbon dioxide sequestration sites [28]:

- Areas located beyond the coal seams belonging to operating coal mines, regardless of depth,
- Minimum depth below 1000 m, preferably 1250–1300 m,
- Methane content above 4.5 $m^3$ $CH_4/Mg_{daf}$, (preferably >8.0 $m^3$ $CH_4/Mg_{daf}$),
- Occurrence of claystone and mudstone formations in the Carboniferous strata above the $CO_2$ storage as well as isolating formations of Carboniferous overburden,
- Low degree of urban development.

The aim of the paper is to present the results of modeling and computer simulations of injecting $CO_2$ into selected coal seams of the Upper Silesian Coal Basin, Poland. On the basis of the developed models, the study discusses a series of simulations of the process of enhanced coal bed methane recovery with a simultaneous sequestration of $CO_2$.

## 2. Materials and Methods

Based on the analysis of geological structures and the deposition of high methane content coal seams in the Upper Silesian Coal Basin, Poland, three promising regions were selected, namely Studzienice, Bzie-Dębina and Pawłowice–Mizerów (see Figure 1).

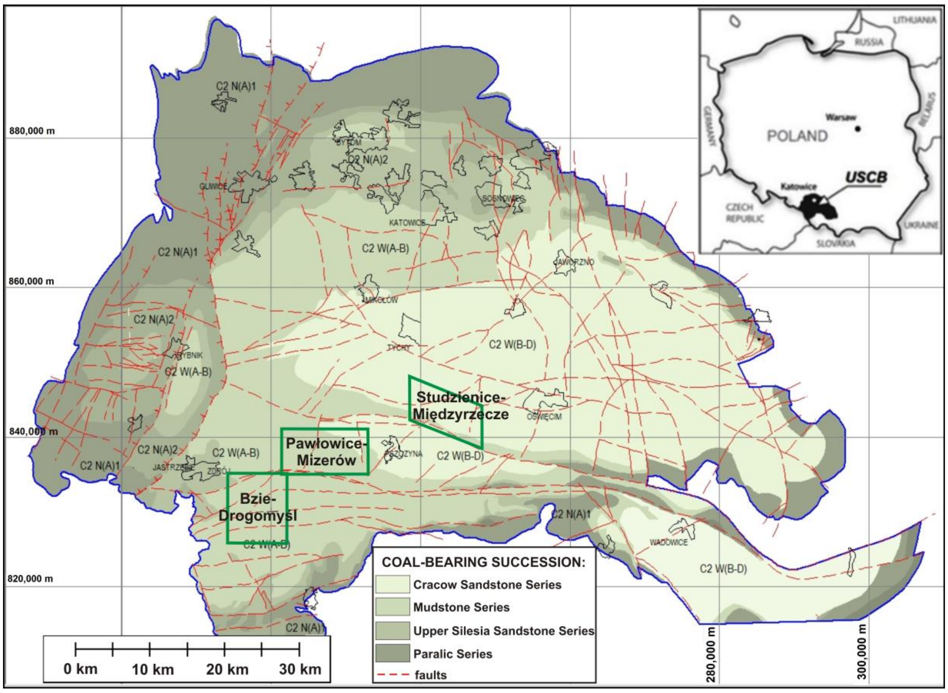



**Figure 1.** Location of the three enhanced coal bed methane (ECBM) promising regions selected for research on $CO_2$ storage in deep coal seams on the geological map of the Upper Silesian Coal Basin (USCB).

Region Pawłowice–Mizerów comprising two coal seams, 405 and 510, was selected for the research activities. Coal seams 405 and 510 deposited at the depth of 1130 m and 2270 m characterize of average methane content of 4.2 $m^3$ $CH_4/Mg_{daf}$ and 3.8 $m^3$ $CH_4/Mg_{daf}$, respectively. For the chosen region, which may constitute a potential $CO_2$ sequestration site, a static model was developed, which takes into consideration the possible occurrence of faults, the lithology of the modeled rock mass as well as the distribution of methane content in the two seams. The above mentioned model was a starting point for the development of a dynamic model encompassing the simulations of injecting $CO_2$ into coal seams using directional drilling.

Coal seam 405, lying at the depth of 1130 m in the designated region of Pawłowice–Mizerów, USCB, Poland, belongs to the mudstone series of Załęskie layers, whereas seam 510 to the saddle layers of the Upper Silesian sandstone series. The coal seam spacing within the discussed region is directed towards East-West, while the seams orientation is towards the North (see Figure 2). The faults that occur in the zone divide the model into 17 blocks, the biggest of which has an area of about 19 km$^2$.

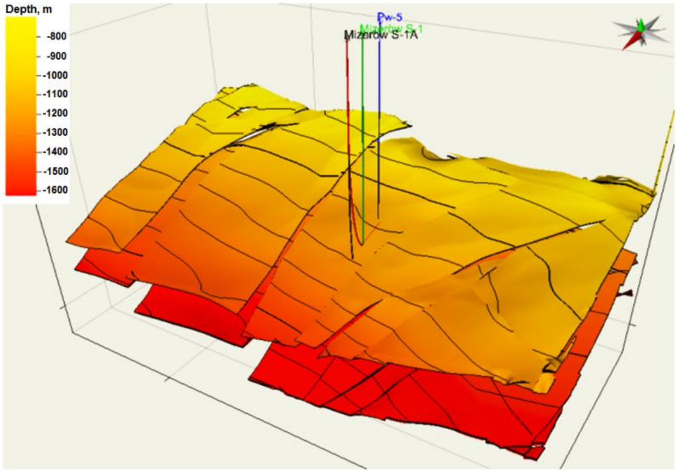



**Figure 2.** Coal seams 405 and 510 as reflected in the model.

For subsequent modeling analyses, a region situated in a tectonic block of 13 km$^2$ was selected. Figure 3 demonstrates the contour of the modeled area along with the distribution of the boreholes, which provided data for the development of the static model. The thickness of the area ranges from 209 to 521 m. A horizontal resolution of the interpolation of 50 m × 50 m was applied. The depth range in the model is from elevation 840 m ASL (depth of approximately 1100 m) to 2021 m ASL (depth of approximately 2275 m).

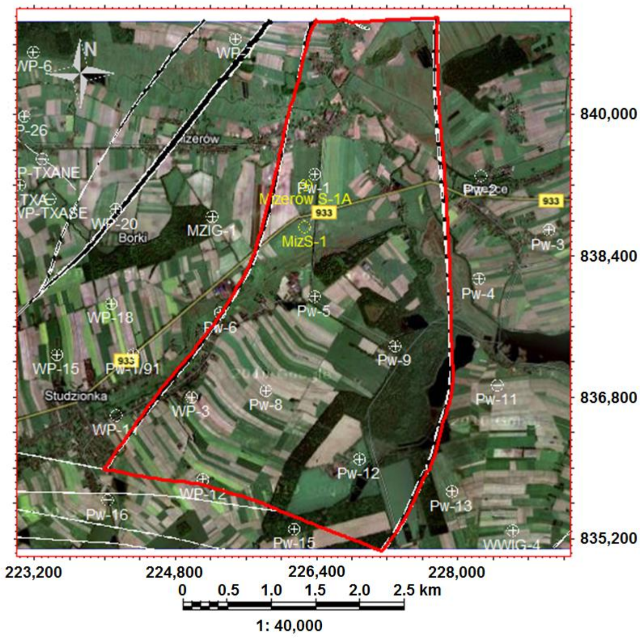



**Figure 3.** The location of the modeled area set against a map of land development with the designated wells, archival bore holes and tectonic blocks.

Data from well logs concerning lithologic types, methane content and the thickness of the drilled rock below the depth of 1000 m were used to develop the model. Before particular lithologic types were entered into the model, they were ascribed appropriate numerical codes. The results of the well interpretations obtained in such a way were subject to the scale up well logs process in a discrete form. For the lithologic data, a statistical algorithm was applied. The algorithm ascribes to the given interval the most frequently represented lithology type within the averaging interval.

## 3. Results and Discussion

During the course of developing the lithology model for Pawłowice–Mizerów region, a sequential indicator algorithm (sequential indicator simulation), belonging to the group of stochastic algorithms, was used. The application of this particular methodology was determined by the quantity of data. A static model was developed including the lithology, the thickness and the methane content of the seams in the selected tectonic block with 15.88% share of bituminous coal. Table 1 and Figure 4 present the modeling results of the lithology in the discussed region.

**Table 1.** The results of lithology modeling in the region of Pawłowice–Mizerów (USCB, Poland).

| Lithology Type | Percentage (%) |
|---|---|
| Bituminous coal | 15.90 |
| Claystone | 44.31 |
| Sandstone | 27.40 |
| Mudstone | 12.15 |
| Conglomerate | 0.23 |

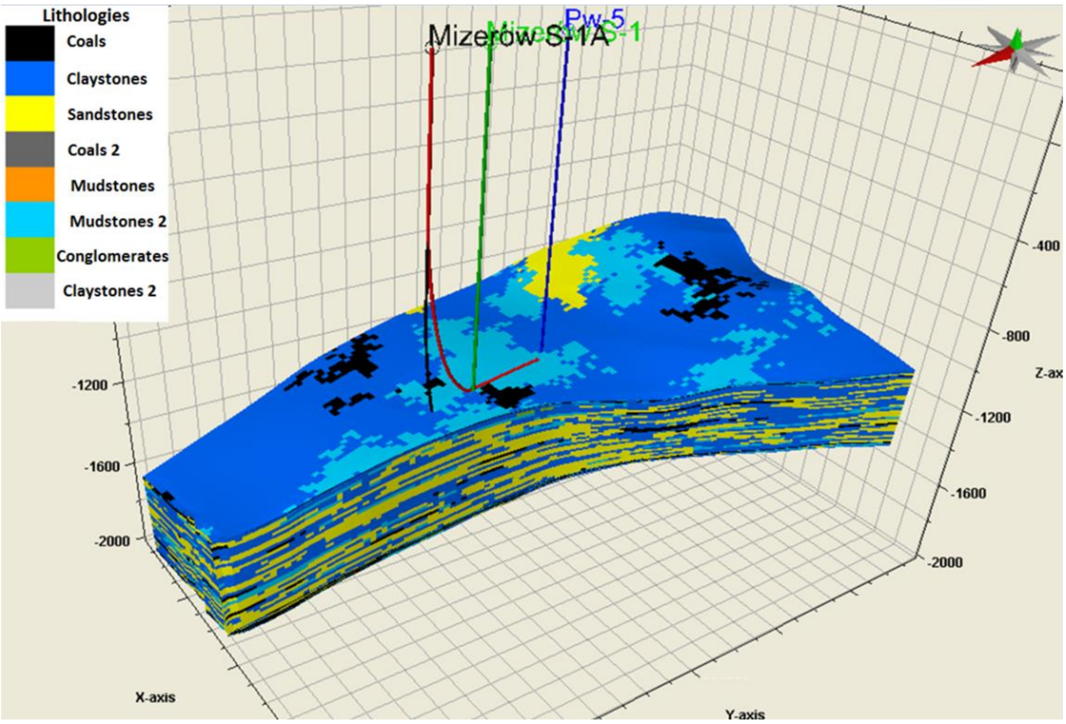
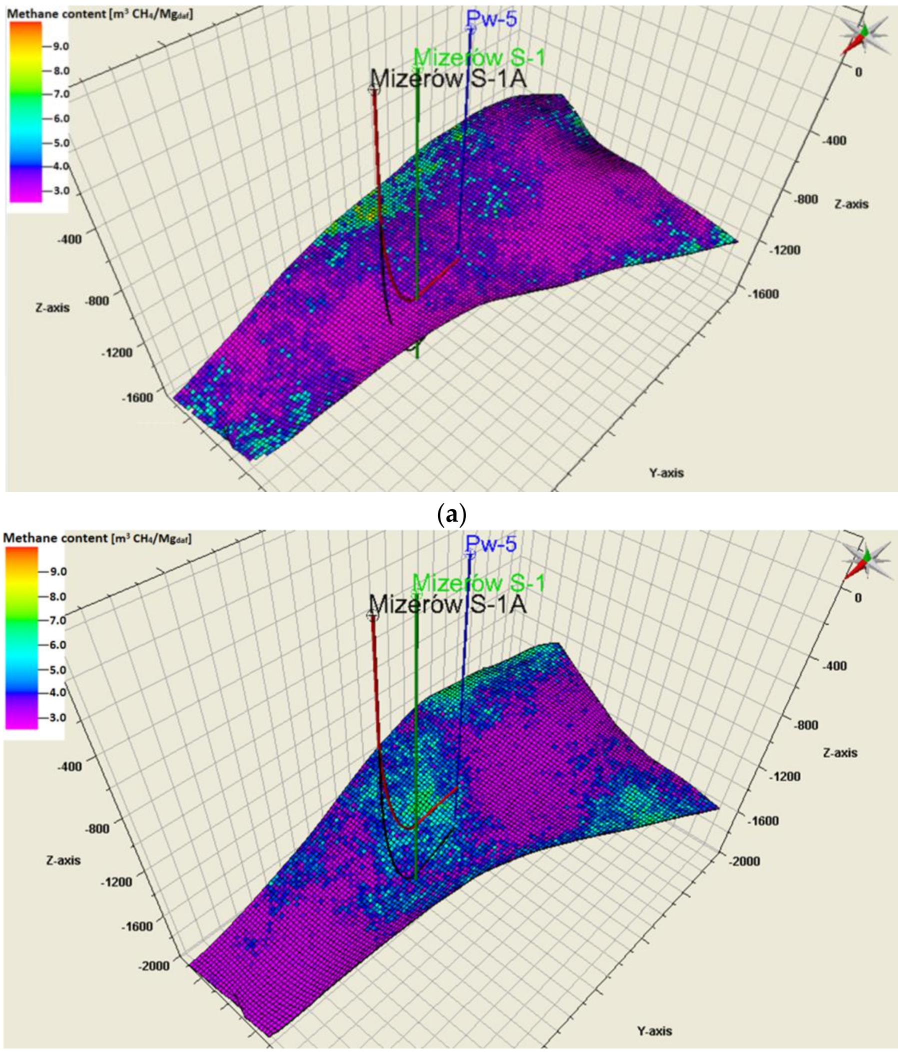



**Figure 4.** A spatial lithology model of Pawłowice–Mizerów region (USCB, Poland).

The methane occurring within the Upper Carboniferous rock mass is genetically bound to coal. In hard coal deposits, methane may occur in the form of sorbed methane (physico-chemically bound to coal substance), as free methane, which fills the coal seam pores and fractures or in gangue where it fills the fault fissures. The occurrence of free methane in coal gangues depends on their volume and porosity, on the degree of pore saturation with gas as well as on the reservoir pressure. The amount of methane sorbed on coal depends mainly on coal sorption capacity, temperature and reservoir pressure. The increase in the degree of carbonation and the pressure as well as the decrease in coal moisture and temperature constitute favorable conditions for the accumulation of methane in the seams. In hard coal deposits, methane occurs predominantly in the form of adsorbed methane. In the developed model, the methane content in the designated coal seams ranges from 2.54 to 10.14 $m^3$ $CH_4/Mg_{daf}$. Table 2 presents data concerning the methane content of seams 405 and 510, i.e., the volumetric amount of the methane of natural origin contained in a weight unit in the body of coal. Figure 5 demonstrates the modeling results of methane content and its distribution in the seams.

**Table 2.** Methane content in coal seams 405 and 510.

| Seam | Methane Content ($m^3$ $CH_4/Mg_{daf}$) | | |
|---|---|---|---|
| | min | max | Average |
| 405 | 2.54 | 10.05 | 4.20 |
| 510 | 2.98 | 6.76 | 3.80 |




(**a**)

(**b**)

**Figure 5.** The distribution of methane content for seams: (**a**) 405 and (**b**) 510.

In the developed numerical model, a series of simulations associated with the injection of $CO_2$ into coal seams 405 and 510 using the horizontal injection well Mizerów S-1A was conducted, whereas bore hole Pw-5 performed the function of a production well (see Figure 6).

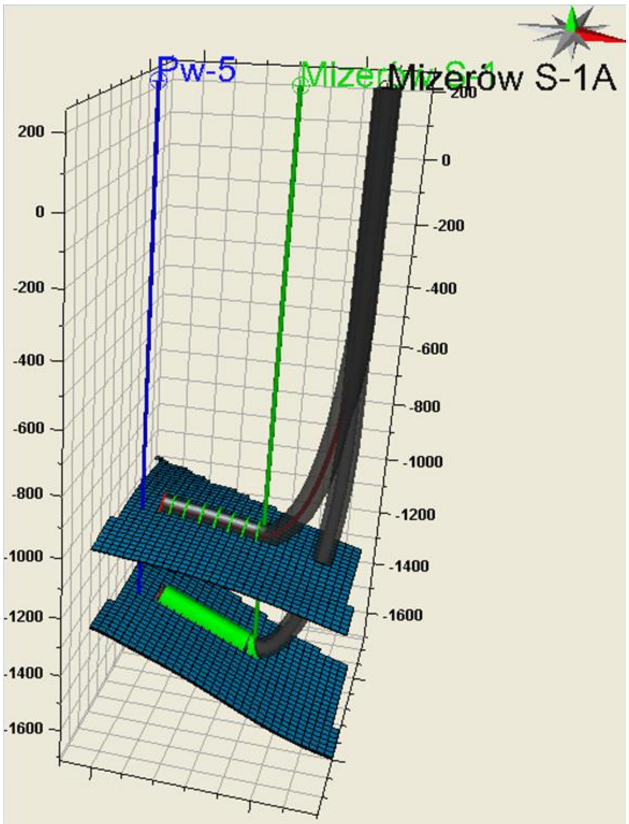



**Figure 6.** The layout of wells in the model of seams 405 and 510.

Table 3 presents the adopted structural model parameters for seams 405 and 510 in the selected block where the simulations were conducted.

**Table 3.** Structural parameters of the model for seams 405 and 510.

| Parameter | Seam 405 | Seam 510 |
|---|---|---|
| Thickness (m) | 3.0 | 8.0 |
| Depth (m) | 1333–1516 | 1640–1967 |
| The area of the model ($m^2$) | 1,836,790 | |
| Horizontal resolution of the interpolation grid (m) | 50 × 50 | |
| Vertical resolution of the model (m) | 1.0 | 2.66 |
| Fracture porosity (%) | 0.5 | |
| Permeability X,Y,Z (mD) | 1.5 | |

The model was constructed on the basis of a regular grid of 50 × 50 blocks. The area of the modeled region totals 1.83679 $km^2$. For the purpose of simulating the injection of $CO_2$ into coal seams 405 and 510, a compositional version of the ECLIPSE (ECLIPSE Reservoir Simulation Software, ver. 2011.3, Schlumberger, New York, NY, USA) simulator with the option of coal bed methane including the phenomena that accompany the process of injecting $CO_2$ into coal seams was used. The above phenomena comprise the major mechanisms responsible for the flow of water and gas within the coal seam, namely the desorption of gas from the coal matrix into the cleat system, diffusion according to

Fick law, Darcy's flow in the fractures, the shrinking and swelling of coal matrix as well as the chemical exchange between $CO_2$ and $CH_4$ molecules.

Coal bed methane is retained in coals in three ways: first, as a free gas within the pore space or fractures in coal; second, as adsorbed molecules on the organic surface of the coal and third, dissolved in groundwater within the coal. Porosity in coals occurs as fracture porosity and matrix porosity. The latter is more significant when considering the CBM retention potential of coals.

The gas generated in excess of that which can be adsorbed on the coal surfaces will be free gas within the porosity of the coal, most notably in the fracture porosity. The fracture porosity in coal is primarily produced due to the formation of fractures called cleat being a joint or a set of joints perpendicular to the top and bottom of the coal seam. Usually, there are two cleat sets developed in an orthogonal pattern. Cleat is a major control on the directional permeability of coals [29].

Simulator ECLIPSE allows for the double porosity in the model. The model consists of two interconnected systems representing the coal matrix and the cleat system. Methane is stored by means of sorption in a poorly permeable coal matrix characterized by varied porosity in comparison to the cleat system where the phenomenon of desorbed gas flow takes place. Accordingly, in double porosity models, the number of layers is doubled, whereas the calculations during the simulation are conducted for a double number of cells.

The model of gas adsorption on coal for the different components is described in ECLIPSE 300 by means of the extended Langmuir isotherm [30]. The adsorption capacity is a function of the pressure and free gas phase composition. For each of the gases ($CO_2$ and $CH_4$), it is required to introduce Langmuir isotherm parameters, i.e., the Langmuir volume constant $V_i$ and the Langmuir pressure constant $P_i$. These parameters are typically determined on the basis of experiments. Different isotherms can be used in different regions of the field. The multicomponent adsorption capacity is calculated by:

$$L(p,\ y_1,\ y_2, \ldots)_i = \theta \frac{P_s}{RT_s}\left( V_i \frac{y_i \frac{p}{P_i}}{1 + \sum_{j=1}^{nc} y_j\ \frac{p}{P_j}} \right), \tag{1}$$

where

$\theta$ = Scaling factor;
$P_s$ = Pressure at standard conditions;
$R$ = Universal gas constant;
$T_s$ = Temperature at standard conditions;
$V_i$ = Langmuir volume constant for component $i$;
$P_i$ = Langmuir pressure constant for component $i$;
$y_i$ = Hydro carbon mole fraction in gas phase for component $i$;
$p$ = Pressure.

For the special case of a single component, the extended Langmuir isotherm is identical to the usual Langmuir isotherm giving the storage capacity as a function of pressure only:

$$L(p) = \theta \frac{P_s}{RT_s}\left( V \frac{\frac{p}{P}}{1 + \frac{p}{P}} \right), \tag{2}$$

where $V$ is the maximum storage capacity for the gas, referred to as the Langmuir volume constant, and $P$ is the Langmuir pressure constant. The constants used in the extended Langmuir formulation can hence be estimated from a series of single-component gas experiments.

Time dependent diffusion in ECLIPSE 300, i.e., the diffusive flow between the matrix and the fracture is given by:

$$F_i = \text{DIFFMF}\ D_{c,\,i}\ S_g\ RF_i\ (m_i - \rho_c\ L_i), \tag{3}$$

where

$m_i$ = Molar density in the matrix coal;
DIFFMF = Matrix fracture (or multi porosity) diffusivity;
$\rho_c$ = Rock density (coal density);
$D_{c,i}$ = Diffusion coefficient (coal) component $i$;
$RF_i$ = Readsorption factor component $i$;
$S_g$ = Gas saturation, for desorption a value of unity is used;
$\rho_c\ L_i$ = Equilibrium molar density of adsorbed gas.

The matrix-fracture diffusivity is given by:

$$\mathrm{DIFFMF} = \mathrm{DIFFMMF} \cdot VOL \cdot \sigma, \quad (4)$$

where DIFFMMF is the multiplying factor input, $VOL$ is the coal volume and $\sigma$ is the factor to account for the matrix–fracture interface area per unit volume.

Often the component's sorption time is a quantity that is easier to obtain than the diffusion coefficients. For desorption we write the flow as:

$$F_i = (VOL/\tau_i) \cdot (m_i - \rho_c\ L_i), \quad (5)$$

where $\tau_i = 1/(D_{c,i} \cdot \mathrm{DIFFMMF} \cdot \sigma)$ is called the sorption time.

The parameter controls the time lag before the released gas enters the coal fracture system. The sorption times are given by the diffusion coefficients, DIFFCBM, and the matrix-fracture interface area, SIGMA, together with the multiplying factor DIFFMMF. If the sorption times are known, a value of unity can be assigned to $\sigma$ and DIFFMMF. The diffusion coefficients can then be assigned to the reciprocal of the sorption times [31].

Simulator ECLIPSE 300 requires predetermining the initial gas concentration in the coal by means of inputting the gas volume to the mass of the base rock ($sm^3/kg$). The ECLIPSE software defines the $sm^3/kg$ unit as a cubic meter of gas (pressure of 1 atm = 1013.25 hPa and temperature of 15.56 °C) per one kilogram of coal under in situ conditions.

In the developed model, laboratory data obtained during the execution of RECOPOL project were used [32]. Detailed parameters used in the simulation are compiled in Table 4.

**Table 4.** Details of the reservoir simulation model.

| Parameter | Seam 405 | Seam 510 | Unit |
|---|---|---|---|
| Initial pressure at the injection point | 110.4–115.7 | 143.4–157.3 | bar |
| Coal density | 1330.0 | | $kg/m^3$ |
| $CH_4$ Diffusion coefficient | 0.0000685 | | $m^2/d$ |
| $CO_2$ Diffusion coefficient | 0.0001390 | | $m^2/d$ |
| Min. Production pressure | 5.0 | | bar |
| Max. Injection pressure | 165.0 | 175.0 | bar |
| **Extended Langmuir Isotherm Parameters** | | | |
| $CH_4$, volume $V_L$ | 0.0205 | | $sm^3/kg$ |
| $CH_4$, pressure $P_L$ | 42.00 | | bar |
| $CO_2$, volume $V_L$ | 0.0320 | | $sm^3/kg$ |
| $CO_2$, pressure $P_L$ | 19.03 | | bar |

The increase in temperature and the pressure of injected $CO_2$ favors the transport of carbon dioxide, thereby enhancing methane recovery; the presence of water in the coal deposit may decrease coal permeability, and, as a consequence delay $CO_2$ adsorption inhibiting the migration of carbon dioxide [33–36].

In the course of the simulations, curves reflecting the relationship between relative coal permeability and water saturation obtained during a pilot CBM project in the Upper Silesian Coal Basin executed by TEXACO were applied [37]. The relationships were used during the stage of dynamic modeling for the purposes of RECOPOL project [38].

A number of simulations of the process of enhanced coalbed methane recovery with the simultaneous injection of carbon dioxide into the coal seam were conducted. Changes of average pressure in the injection zone, flowrates of $CO_2$ injection and the daily production rates of water and methane were recorded during the simulation (Figures 7 and 8).

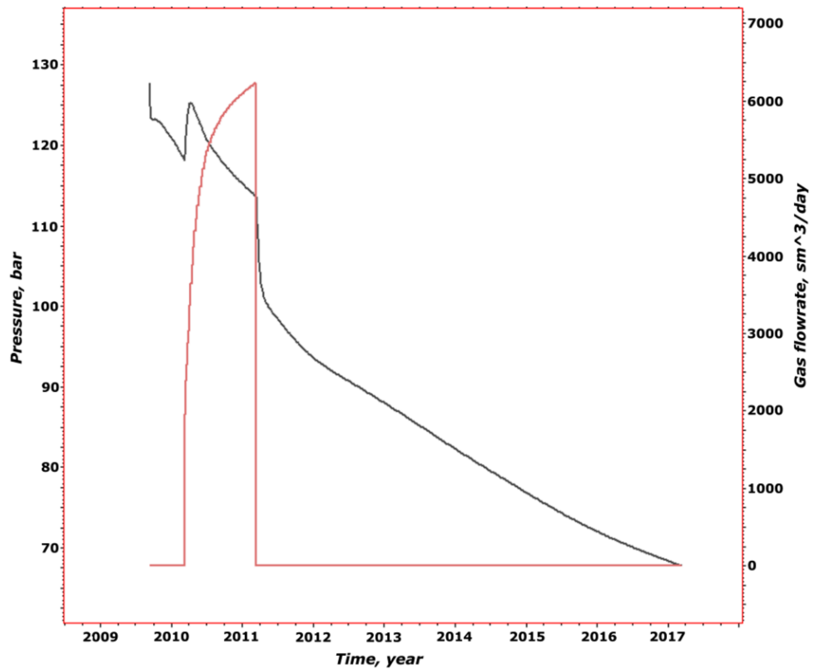



**Figure 7.** Changes of average pressure in the $CO_2$ injection zone (black line) and daily $CO_2$ injection flowrate (red line).

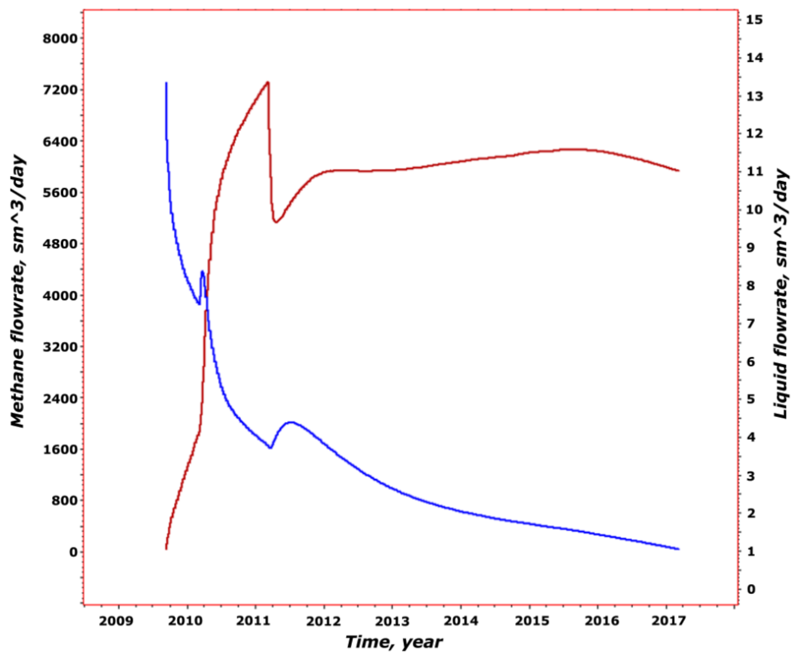



**Figure 8.** Daily production rates of water (blue line) and methane (red line).

Figure 7 shows the changes of average pressure in the $CO_2$ injection zone and the daily flowrate of the $CO_2$ injection. In the simulation, three intervals of time were separated. During the first six months of the simulation, water is produced from the coal seam, which causes the decrease of pressure in the reservoir. The fall of the pressure initiates methane desorption from the coal matrix (Figure 8). After six months from the start of the simulation, the injection of $CO_2$ into the coal seam begins and lasts uninterruptedly for one year. In the first month of injection, a sudden increase in pressure can be observed, but in the following months a marked drop in pressure is noticeable. Figure 7 shows a significant decline in reservoir pressure after the end of $CO_2$ injection. Moreover, the decrease of methane production and the increase of water production can be observed in the first month after the end of the $CO_2$ injection (Figure 8). The simulation of the process of gas migration after the injection has been finished is continued for 5 years. At that time, a constant drop of reservoir pressure can be observed to the end of simulation (Figure 7). Moreover, Figure 8 presents the stabilization of methane production and a decrease in its efficiency in the final phase of the simulation.

The results of the simulations demonstrate that the aggregate amount of carbon dioxide injected into coal seam 405 during the period of one year totaled 1,954,213 $sm^3$. The aggregate amount of water obtained from the production wells during the whole period of the simulations (6.5 years) totaled 9867 $sm^3$. At the same time, 15,558,906 $sm^3$ of gas was extracted, out of which 14,445,424 $sm^3$ constituted methane. The remaining 7% of the recovered gas was carbon dioxide obtained as a result of reverse production of previously injected $CO_2$.

A similar phenomenon related to reversed $CO_2$ production of approximately 9% of the injected gas was observed during a field experiment of $CO_2$ storage in underground coal seams with simultaneous (enhanced) production of coalbed methane in the RECOPOL project performed in the years 2003–2005 in the Upper Silesian Coal Basin, Poland. During the $CO_2$ injection into the coal seam, a slow rise of the $CO_2$ content in the production well was observed, which could be attributed to the injected $CO_2$. In addition, a decrease in total gas production was observed during longer fall-off periods in the injection well. This indicated a clear response of the production well to the injection activities. After the stimulation of the injection well, the gas production increased rapidly and $CO_2$ concentration in the production gas also rapidly increased. It clearly indicated the breakthrough of the gas. The amount of the injected $CO_2$ that was produced back by the production well, mainly after the frac job, was estimated to amount up to 68 tones. The amount of the produced $CO_2$ was much lower (about 9%) than the amount of circa 692 tons of injected $CO_2$ into the reservoir [39].

The results of numerical simulations show that part of the $CO_2$ injected into the coal is adsorbed by coal matrix, and the remaining part causes the formation and development of a $CO_2$ zone in the system of fractures around the injection well. The changes in saturation of $CO_2$ and $CH_4$ in the fracture system after one year of $CO_2$ injection are presented in Figure 9 in the form of mole fractions of two components of the gas mixture filling the fractures of coal. Figure 10 presents the saturation of gases in the coal matrix after 1 year of $CO_2$ injection.

The water saturation of the coal seam decreases from the initial 100% to approximately 45% after 1 year of $CO_2$ injection in the final stage of the simulation (Figure 11a)., whereas gas phase saturation of the cleat system ranges from 0% to about 55% (Figure 11b). Figure 12 presents water and gas phase saturation in the fractures after 5 years from the end of $CO_2$ injection.

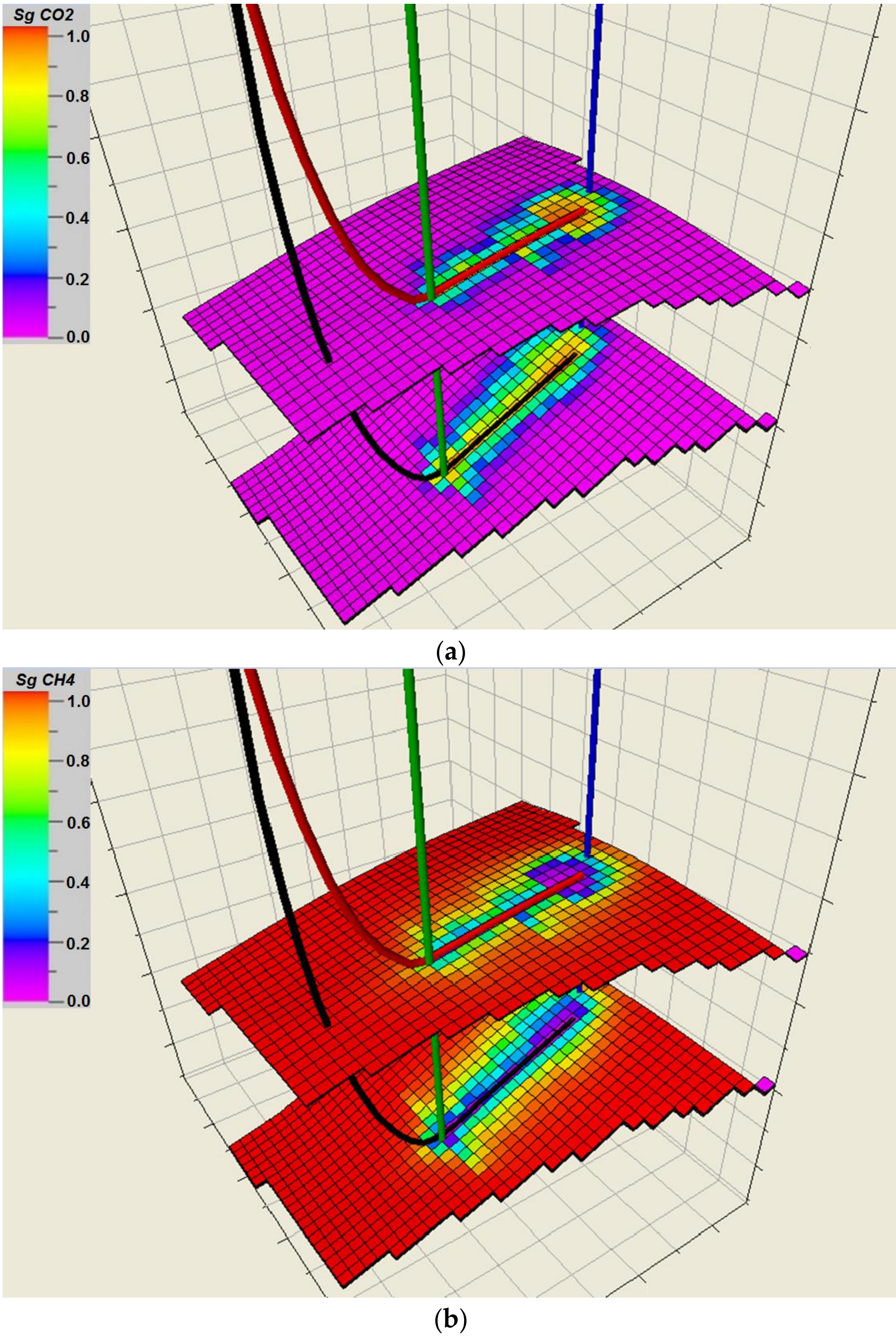
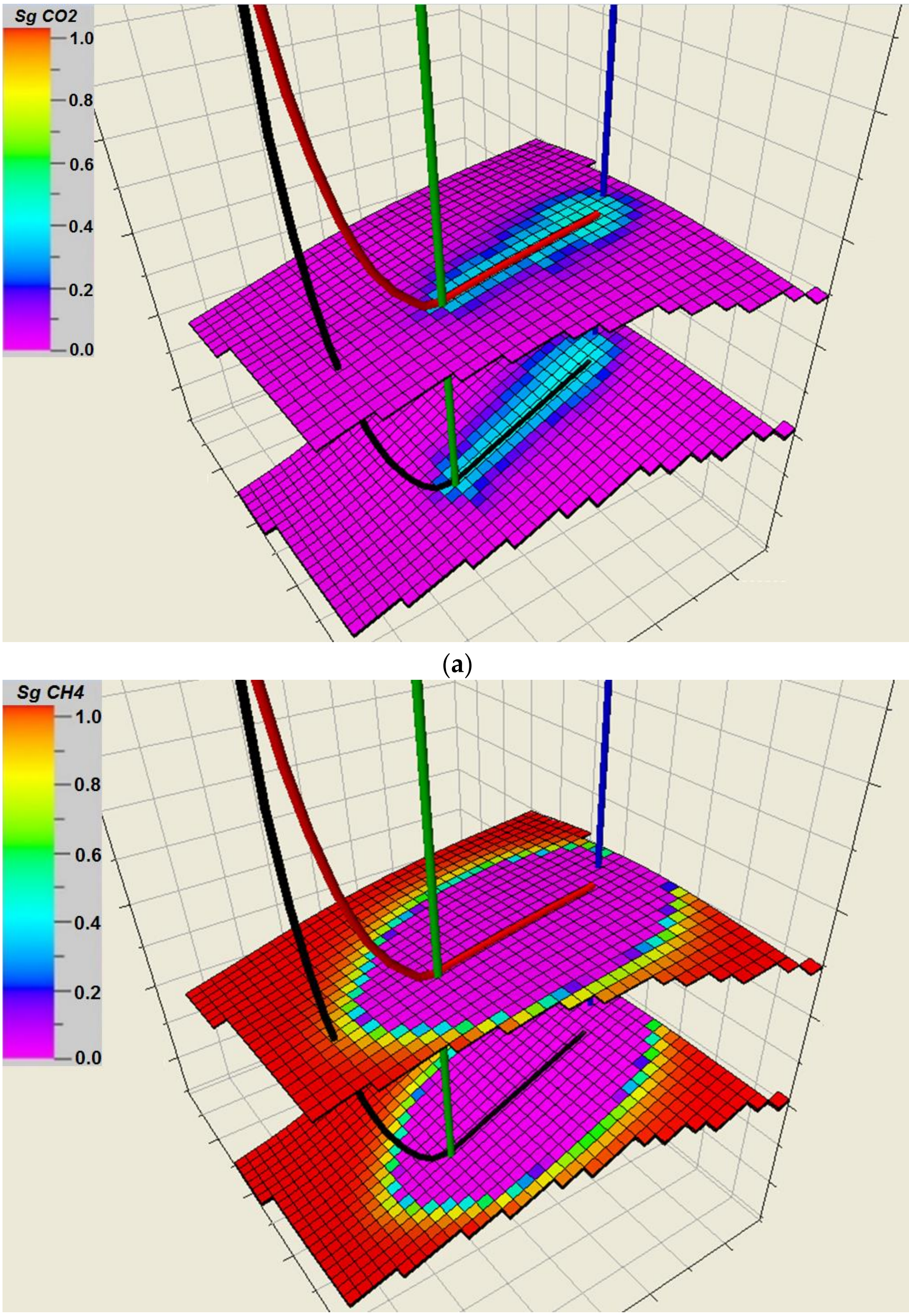


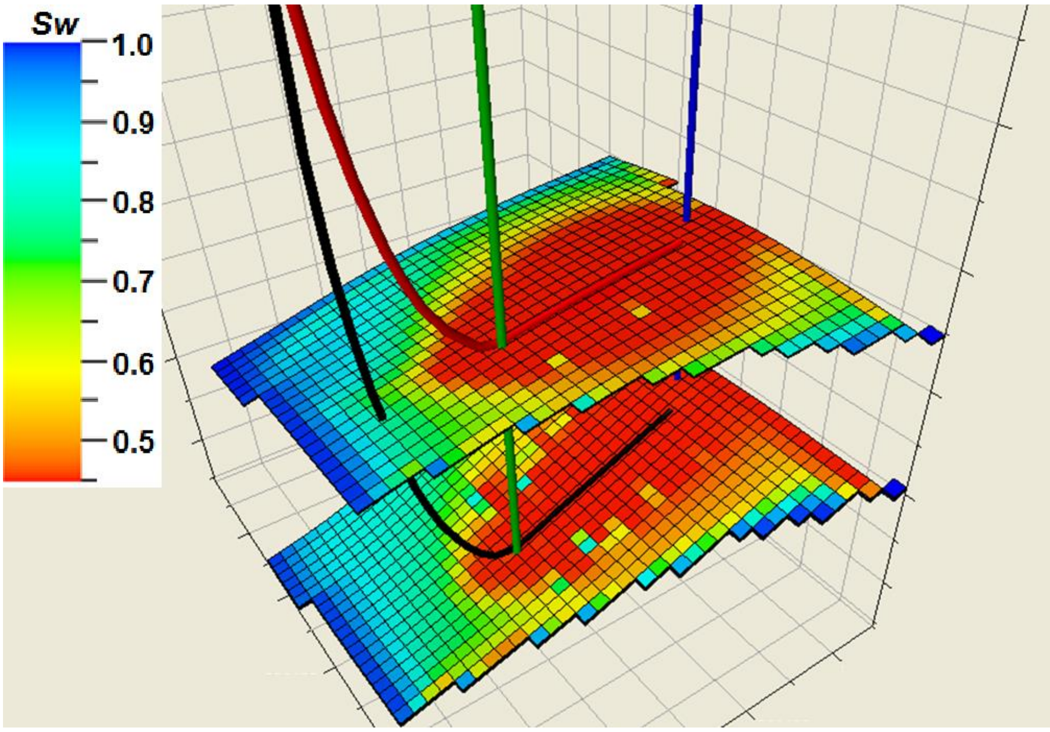

**Figure 9.** Changes in gas saturation-*Sg*: (**a**) $CO_2$ and (**b**) $CH_4$ in fractures after 1 year of $CO_2$ injection (mole fractions of gases in fractures).



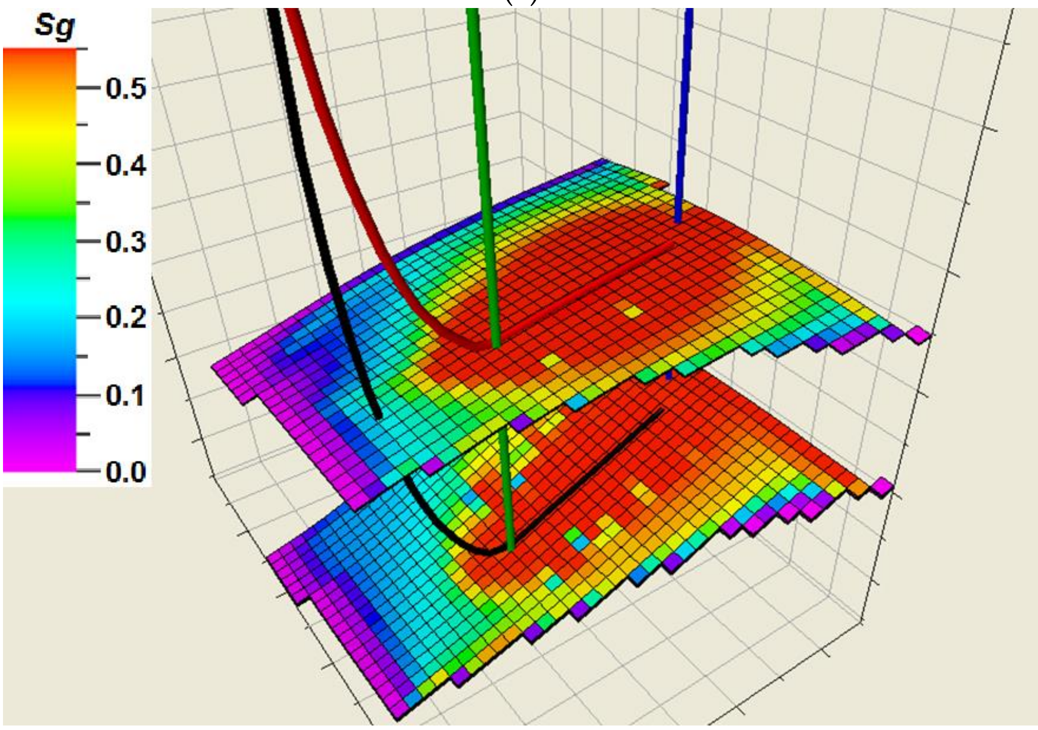

(**a**)

(**b**)

**Figure 10.** Changes in gas saturation-*Sg*: (**a**) $CO_2$ and (**b**) $CH_4$ in coal matrix after 1 year of $CO_2$ injection. (mole fractions of gases in coal matrix).

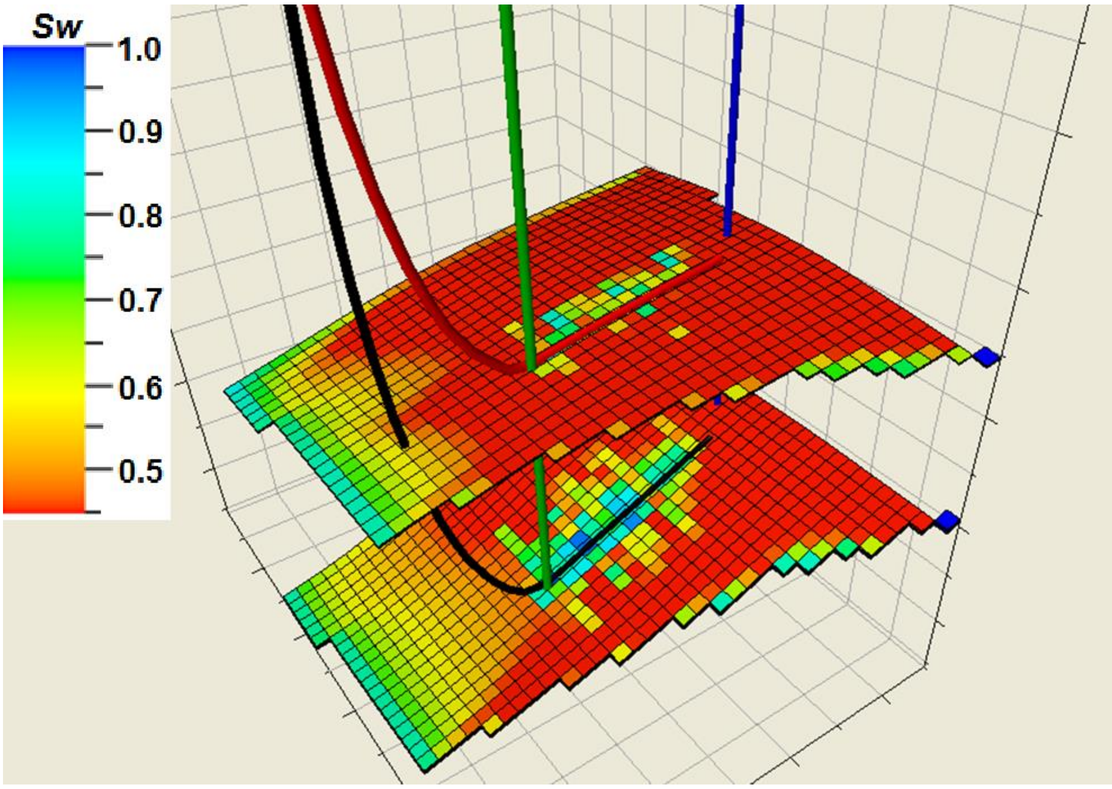



(**a**)

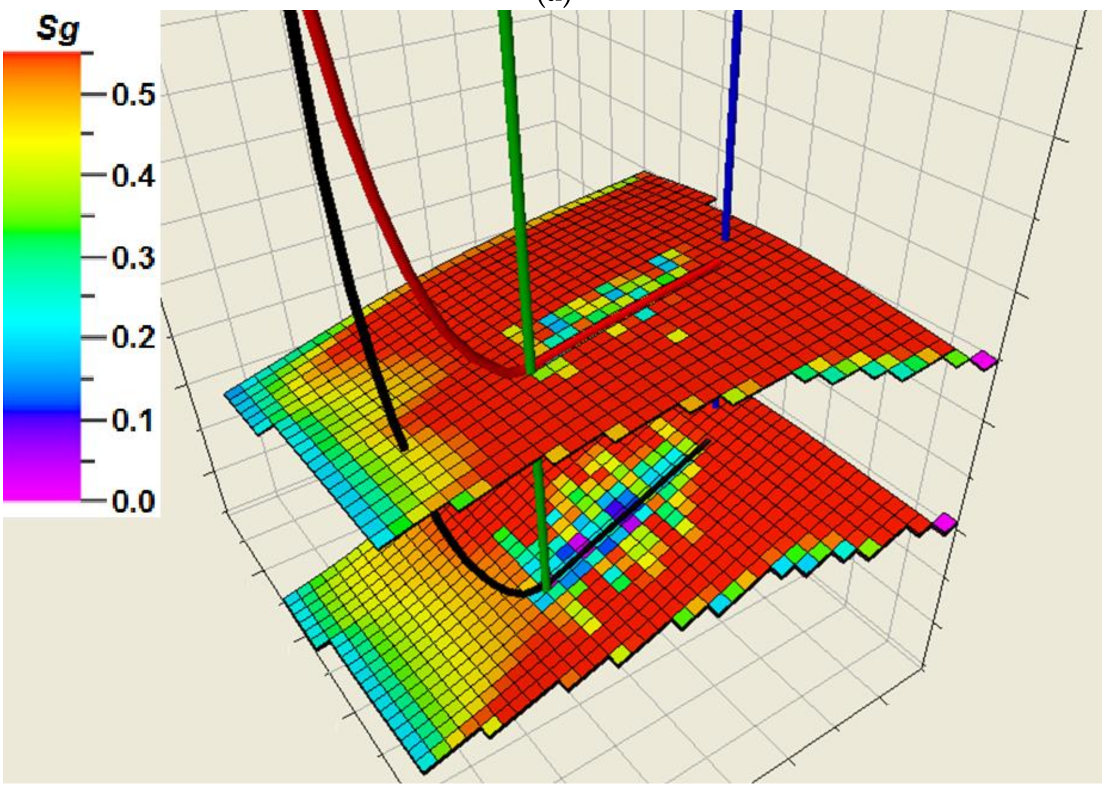



(**b**)

**Figure 11.** Changes in water saturation—*Sw* (**a**) and gaseous phase—*Sg* (**b**) in the fractures after 1 year of $CO_2$ injection.




(**a**)




(**b**)

**Figure 12.** Changes in water saturation—*Sw* (**a**) and gaseous phase—*Sg* (**b**) in the fractures after 5 years from the end of $CO_2$ injection.

Coal cleats are natural fractures whose orientation is connected with the occurrence of tectonic stress during the coalification processes. Coal permeability is mainly related to the system of cleats within the coal structure. During the process of injecting $CO_2$ into the coal seam under supercritical conditions, it may be expected that pore and fracture permeability will increase, especially in the case of large depth storage [21]. Coal permeability may be significantly affected by the changes of relative permeability, which is highly dependent on the degree of rock saturation, on the effective stress exerted on the coal seam as well as on the pore pressure, which causes the coal matrix shrinking and swelling.

The process of methane production from a coal seam is accompanied by two different phenomena closely linked with the gradual drop of the pressure within the seam, which have a negative impact on coal permeability. The first one is rock mass compression causing the increase in the effective stress in the horizontal direction and the decrease in coal permeability. The other one is the phenomenon of methane desorption, which results in the shrinking of coal matrix, thereby decreasing the horizontal stress and increasing coal permeability.

In the case of enhanced methane recovery by means of carbon dioxide injection, the adsorption of $CO_2$, which has a bigger sorption capacity than methane, takes place. The phenomenon of $CO_2$ adsorption may lead to the swelling of coal matrix, which has a negative impact on the permeability of the cleat system. It was reported that the phenomenon of coal matrix shrinking associated with the desorption/adsorption of $CO_2$ is from two to five times bigger in comparison with methane [40]. For this reason, the decrease in coal permeability caused by the shrinking of coal matrix as a result of injecting $CO_2$ is of bigger importance than the increase in coal permeability connected with the matrix shrinking during the primary production of methane [41]. The presented results of the simulations for seam 405 in the Upper Silesian Coal Basin demonstrate that the amount of the injected carbon dioxide significantly decreases after the phenomenon of coal matrix shrinking and swelling has been taken into account in the calculations. It was observed that the aggregate amount of the injected carbon dioxide decreases in such a case by approximately 68%. Figure 13 presents the daily $CO_2$ injection rate both with and without taking into consideration the phenomenon of coal matrix shrinking and swelling.

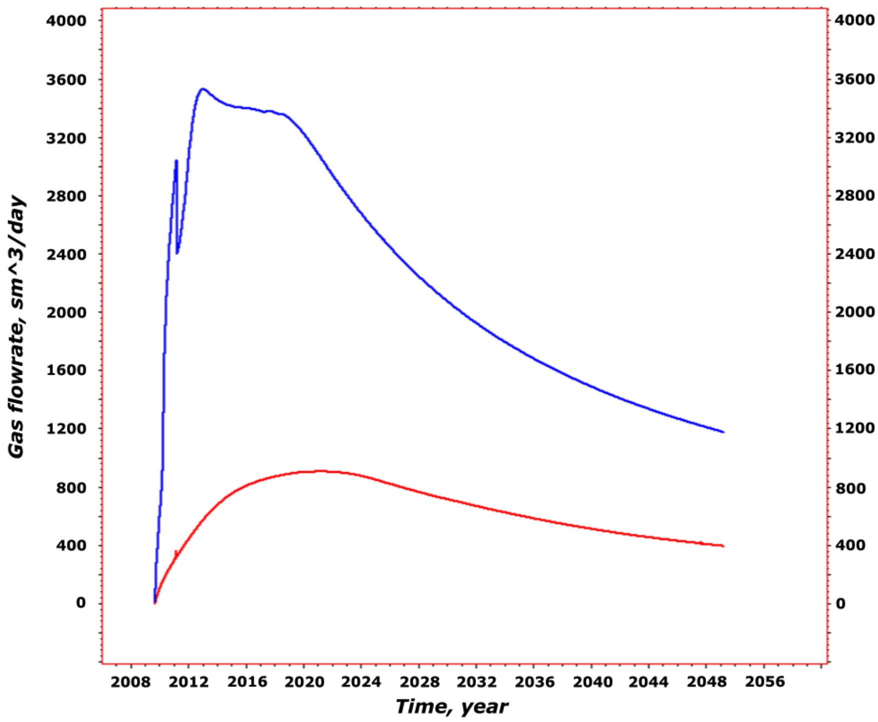



**Figure 13.** Daily $CO_2$ injection rate (the red color signifies the results of the simulation taking into account the phenomenon of coal matrix shrinking and swelling, while the blue one represents the simulation results, which do not include the phenomenon).

A number of researchers have investigated coal matrix deformation in laboratory experiments using methane, carbon dioxide and other gases [42–46]. In the majority of these studies, $CO_2$ was found to cause the swelling of coal matrix of the order of two to five times greater than methane. Moreover, simultaneous measurements of coal matrix swelling and permeability under $CO_2$ injection [47] have shown that the swelling of matrix caused by $CO_2$ injection has a severe impact on coal permeability, confirming the outcome of ECBM field pilots. For example, the loss of injectivity was experienced in the RECOPOL field experiment both before the hydraulic fracture treatment was performed and afterwards, especially during the periods when continuous injection was temporarily interrupted. The decrease in injectivity was attributed to coal swelling, but this could not be proven in the field. Other possible explanations include the clogging of the wellbore perforations or of the near-well zone by clays, precipitation of mineral scaling and the collapse of the cleat network around the well. Although such effects cannot be excluded, it can be inferred from laboratory experiments on coal based on the material from the RECOPOL site [48,49], that coal swelling certainly played a significant role in the reduction of permeability in the RECOPOL field test. To overcome this problem, there is a clear need for an operational strategy to control or avoid the permeability loss caused by coal swelling during the ECBM operations.

## 4. Conclusions

The study presents the results of modeling 3D distributions of gas and water phases within the cleat system assuming phase equilibrium, the distribution of the saturation of $CO_2$ and $CH_4$ in the coal seams as well as the process of gas migrations during particular stages of the simulation. The results of the simulations demonstrate that the aggregate amount of carbon dioxide injected into coal seam 405 during the period of one year equaled 1,954,213 $sm^3$. The aggregate amount of water obtained from the production wells during the whole period of the simulations (6.5 years) totaled 9867 $sm^3$. In parallel, 15,558,906 $sm^3$ of gas was extracted, out of which 14,445,424 $sm^3$ constituted methane.

The remaining 7% of the recovered gas was carbon dioxide obtained as a result of the reverse production of previously injected $CO_2$. Having taken into account the phenomenon of the shrinking and swelling of coal matrix, it was observed that the aggregate amount of the injected carbon dioxide decreased by approximately 68% to the level of 625,000 $sm^3$.

The series of computer simulations conducted in this study enable to observe the changes in the parameters of bituminous coal resulting from the injection of carbon dioxide into the seam. However, a detailed analysis of the selected region in terms of its suitability for coal seam $CO_2$ storage requires further analyses including the sorption, geotechnical and other parameters.

The results of the simulations confirm the possibility of enhancing coalbed methane recovery by means of carbon dioxide injection (ECBM). In the discussed region, a 50% increase in methane extraction was observed in comparison to CBM technology. With regard to the observed significant impact of $CO_2$ injection on coal permeability connected with a decrease in the process effectiveness, it is necessary to apply hydraulic fracturing of the coal seams in order to increase the efficiency of the ECBM technology.

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