Field experiment of CO₂-ECBM in the Upper Silesian Basin of Poland

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Abstract
A field experiment of CO₂ storage in underground coal seams with simultaneous (enhanced) production of coalbed methane production was set-up and performed in Poland. An existing CBM well was put back into production to establish a baseline production. A new injection well was drilled 150 m away from the production well. A breakthrough of the injected CO₂ in the production well was considered essential for understanding the operational results. First injection of CO₂ took place in August 2004 in three seams of Carboniferous age. Continuous injection, circa 12-15 t/d, was eventually reached in April 2005 after stimulation of the reservoir by a frac job. Compared to baseline production, the production of methane increased significantly due to the injection activities. Recovery of methane is, however, low which is probably related to low diffusion rates into and out of the coal. Nevertheless, a total of 692 tonnes of CO₂ are stored in the reservoir, most likely due to adsorption of CO₂ on the coal. The results provide good hope for successful future upscaling of the operations and can possibly help to overtake start-up barriers of future CO₂ storage initiatives in Europe.

Keywords: CO₂, coalbed methane, ECBM

Introduction
Technology options are required that will allow for the continued use of fossil fuels without substantial emissions of CO₂. Subsurface storage of CO₂ in geological systems is considered as one promising perspective, which is currently being investigated world-wide. In general, the research window for projects on subsurface CO₂ storage has slowly but surely shifted from desk studies to demonstrations. One of the options considered in this context is the storage of CO₂ in underground coal seams. The injection of CO₂ into coal while simultaneously producing coalbed methane (CBM) combines the production of a “clean”, hydrogen-rich fossil fuel (methane) with CO₂ sequestration. This paper gives an overview of some of the results obtained in the first European field demonstration in Poland, following earlier publications in the GHGT-proceedings [1, 2]. The main goal of this project, co-funded by the European Commission, is to demonstrate that CO₂ injection in coal under European conditions is feasible.

Location
The Upper Silesian Basin in Poland (Figure 1) was considered as the most suitable coal basin in Europe for the application of ECBM. The principal targets in the area are coal seams between 1.3 and 3.3 m thick of Carboniferous age in the depth interval between 900-1200 m. The coal is high-volatile bituminous with a rank of about 0.8-0.85 %Rr. The Carboniferous deposits are disconcordantly covered by circa 200 m thick Miocene shales.

CO₂ injection
A new injection well was drilled in the summer 2003 at 150 m from the existing production well to a depth of 1120 m. After the completion of the pilot site in 2003, first injection tests with water took place in the beginning of July 2004. Liquid CO₂ from an industrial source has been injected since August 2004. From the start, it was not possible to maintain continuous injection with the applied pressures and injection rates.
Required injection pressures appeared higher than initially anticipated. In the course of the project the pressure was increased, however, without achieving continuous injection. In order to learn about the reservoir behavior, both well head and downhole pressure and temperature data were recorded and evaluated. Several actions were taken to establish continuous injection, which was eventually reached in April 2005, following a frac job of the coal seams. Stimulation was required because the permeability of the coal seams reduced in time, presumably due to swelling as the result of contact with the CO₂. Similar observations were made in Canada and the United States, where they were also attributed to swelling of the coal seams [3, 4, 5]. After fraccing circa 12-15 tonnes per day were injected in continuous operation from late April to early June. In total circa 760 tonnes of CO₂ were injected between August 2004 and the end of June 2005 (Figure 2).

Gas production
The coal seams have fairly good gas content (ca. 10 m³/t daf), although diffusion rates are low as shown by desorption tests. The existing coalbed methane production well was cleaned, repaired and put back into production at the end of May 2004, to establish a baseline production. Gas was produced from the
production well to evaluate possible enhancement of the gas rates. The anisotropy of the permeability due to the cleat orientation was thought to hamper an early breakthrough, because the highest permeability is perpendicular to the flow direction. Unexpectedly, a slow rise in the CO₂ content in the production gas was observed since November 2004 which could be attributed to the injected CO₂. In addition, a decrease in total gas production was observed during longer fall-off periods in the injection well. This indicates a clear response of the production well on the injection activities. In April 2005, after stimulation of the injection well, the gas production increased rapidly after a few days. The CO₂ concentration in the production gas also rapidly increased, clearly indicating the breakthrough of the gas. However, the amount of daily produced CO₂ was much lower than the amount of daily injected CO₂, indicating a clear sink of CO₂ in the reservoir. The amount of the injected CO₂ that was produced back by the MS-4 production well, mainly after the frac job, was estimated to amount up to 68 tonnes. The amount of produced CO₂ was much lower (ca. 9 %) than the amount of injected CO₂, indicating a clear sink of circa 692 tonnes or CO₂ in the reservoir. This sink was confirmed by the rapid decrease of production rates after continuous injection stopped in June 2005.

The concentration of methane in the production gas, initially around 95%, dropped significantly after the breakthrough of CO₂ in April 2005. Nevertheless, the absolute amounts of CH₄ that were produced are significantly higher than the estimated baseline production with conventional production (Fig. 3). An increase of circa 70% was estimated between 1st of August 2004 and 28th of April 2005. After the frac job, an increase of circa 55% was estimated. It can therefore be concluded that the injection activities had a positive effect on the gas recovery within the project lifetime, probably due to exchange reactions.

![Figure 3](cumulative.png) Cumulative amount of produced methane in time in the RECOPOL project. The positive effect of the injection activities on the gas production is clearly visible once compared to the projected baseline production.

Shut-in tests of the production well in June 2005 and measurements of the water level in June 2005 showed that the reservoir pressure around the production well was slightly increased compared to the initial pressure but was returning to its equilibrium level. This also seems to confirm that around the production well adsorption of CO₂ is taking place. The gas that was produced after the shut-in test showed a significant increase in the methane concentrations, indicating that the exchange of CO₂ for methane is taking place in the reservoir. Sufficient time is required to allow for diffusion of the gas into and out of the coal matrix. This seems to be confirmed by the decrease in enhancement after the frac job
The enhancement factor is decreasing as a result of the higher injection rates after the frac job, i.e., while the frac job helps in getting the CO₂ into the reservoir and is good from the storage point of view, it actually decreases the amount of methane produced. A probable explanation is that at higher injection rates the time for exchange and adsorption reactions is decreased. The contact time between the coal and the CO₂ was higher before the frac job, allowing diffusion of the gas into and out of the coal matrix.

Despite the enhancement the produced amounts and the recovery factor are very low, probably due to the low diffusion in the coal as shown by the desorption tests. However, it must be emphasized that high production rates were not the primary goal of the RECOPOL project. Only a limited number (3) of coal seams were completed because of the research character of the project.

**Monitoring**

Monitoring of soil gas was performed at four locations in the surroundings of the MS-3 well to detect the unlikely leakage of CO₂ to the surface (Figure 4). Infrared CO₂ sensors were placed in 2m deep tubes and connected to a registration unit. Continuous digital data registration resulted in baseline profiles, this registration continued after the start of the CO₂ injection. The observed variation in the CO₂ concentration could largely be explained by meteorological parameters. Especially, atmospheric pressure and rain events appeared to be dominant. In addition, there are indications for a seasonal dependent influence of root respiration on the measured CO₂ concentrations. So-far, there does not appear to be a contribution from the deeper subsurface, which could possibly be linked to the injected CO₂. Spatial variation between the locations was observed, that can probably be attributed to differences in the shallow subsurface (e.g. peat occurrences) and surface activities (e.g. in a nearby gravel pit).

Coal is actively being mined on the western site of one of the bounding faults of the triangular block where the RECOPOL site is located (Figure 1). Numerical models showed that it is unlikely that the injected CO₂ would leak through the fault into the long walls or mine galleries. Nevertheless, it was decided to monitor the CO₂ concentration in the long walls and galleries anyhow to be absolutely sure. Additionally, it was decided to monitor the CO₂ concentration in those galleries that were sealed off by a dam. The baseline data show that the variation in the measurements is significant. The concentration of CO₂ in the mine (0.1-0.2 %) is controlled by the ventilation regime that is followed in the mine; no relation could be found with the injection activities in the RECOPOL site. The CO₂ concentrations behind the dam (up to 10%) are most likely due to oxidation of the exposed coal in the gob zone that is connected with the sealed space. Isotope analysis indicates a clear biogenic origin of the gas.
Based on the results and the extensive datasets that were collected of the soil and the mine it was concluded that the occurrence of leakage of the injected CO$_2$ to the mine in the overburden and/or to the surface is very unlikely.

**Discussion**

Several months of injection showed that injection without stimulation is difficult under the local field conditions. It was expected that a small additional pressure above the reservoir pressure would be sufficient to establish continuous injection, but this was clearly not the case. The injection pressures required were nearly twice the reservoir pressure. Apparently, this was the result of a decrease in permeability of the reservoir during injection, most likely due to swelling of the coal. These observations are in line with the observations in Canada and the United States. Laboratory experiments on cores have shown that coal swelling can indeed cause a significant decrease in permeability (Mazumder, pers. com.).

In November 2004 an unexpected early breakthrough of the injected CO$_2$ occurred in the production well. This breakthrough was unexpected for the following reasons: 1) the high permeability cleats are oriented perpendicular to the flow line between the wells; 2) numerical modeling indicated that the injected volume until November 2004 was insufficient to result in breakthrough; 3) CO$_2$ was expected to be adsorbed by the coal; 4) CO$_2$ injection was expected to result in a reduction in permeability. Conclusively, the observations show that it is very difficult to get the CO$_2$ into the reservoir, but that once it is injected, it is able to flow relatively fast towards the production well. Transport through high permeability streaks (small sand channels, fractures) is unlikely, because by far the most of the CO$_2$ remains in the reservoir (see below). The most plausible explanation is the existence of a very low permeability zone around the injection well, while the permeability is higher outside this zone. The frac job was able to connect the wellbore compartment with the zone of higher permeability, explaining the increase of injection rates after the frac job. However, once the system is given time to diffuse and re-equilibrate, the zone of low permeability is extending, as is shown by the increase in stabilization pressure in April and June 2005.

**Conclusions**

Advances were made in the understanding of the process that allows improvements in the dedicated numerical simulators. Enhancement of methane production was proven, although the underlying process is not fully understood. Further field experiments and laboratory studies should be undertaken to gain further knowledge of the processes involved. The permeability of the coal remains a critical factor, even though it is shown that the injectivity in low permeability coal could be increased to substantial rates. The injected amounts provide a good basis for a future upscaling of the operations. It is expected that in the Upper Silesian Basin locations can be found with higher permeability, thicker seams and higher gas content, providing a better prospectivity for gas production. With the experiences of this project, field optimization can be performed to enhance production in future sites. Since the process appears to be diffusion-controlled, an optimum distance should be chosen between the wells that guarantees sufficient contact time between the injected CO$_2$ and the in situ coal. Other well completions, such as horizontal or “fishbone” drilling, need to be researched to assess their impact on injectivity and productivity. To enhance the recovery factor even further, dedicated operational schemes, with varying injection and production intervals, should be planned. Operational flexibility in the applied pressure and flow rates is highly recommended to manage the swelling effects.

Conclusively, the consortium showed that it is possible to set up the first on-shore CO$_2$ storage pilot in Europe and to handle all “soft” issues (permits, contracts, opposition, etc.) related to this kind of innovative projects. The lessons learned in this operation can possibly help to overtake start-up barriers of future CO$_2$ storage initiatives in Europe.
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References