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Report and modeling of the MOVECBM field tests in Poland and Slovenia

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Abstract

The MOVECBM field pilot project, which is the successor of the RECOPOL project, has been completed. Here, we summarize the main results from the field tests in Poland and Slovenia. In the RECOPOL project, the CO_2 has been injected continuously over a period of two months into the coal seam. In MOVECBM, the focus is on the verification of containment of the CO_2 herein. The injector has been back-produced and the gas composition has been analyzed. The CH_4/CO_2 ratio of this gas was higher than expected. Flow rates were very low indicating coal swelling. Next to the field pilot in Poland, several lab studies were conducted at several universities (Mons, RWTH-Aachen, U-Utrecht and SKLCC-CAS) determining the key coal parameters for modeling the field tests.
Also, a CO_2 injection experiment was conducted in the Velenje mine in Slovenia (1 injector + 3 producers). Coal swelling was observed during CO_2 injection, which totally impaired the flow into the coal seam. However, weeks after the experiment improved pressure communication between the injector and producers was observed indicating that CO_2 injection had created new fractures in the coal.

Keywords: CO2 injection, ECBM, field pilot, reservoir simulation, coal mine, coal swelling

1. Introduction

Today the production of coal seam gas (CBM) is mature and a growing business worldwide. The CBM production can be enhanced by injecting CO_2 into the coal seam, so called enhanced coalbed methane (ECBM). ECBM has a double goal: the enhanced production of methane and the storage of CO_2 in coal beds. Contrary to for example CO_2-EOR, CO_2-ECBM is far from mature as is pointed out by White et al. [1] in his review on the status of the ECBM technology.

Worldwide only one large-scale pilot has been conducted in a producing CBM field. Starting in 1996, Burlington Resources injected CO_2 for 5 years to enhance their CBM production [2,3]. The methane production was enhanced and at the same time the CO_2 was stored in the coal. Following the Burlington pilot, a few small other ECBM pilots have been conducted worldwide [4] among which the RECOPOL pilot in Poland. The previous study on the

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RECOPOL pilot [5] showed that CO_2 injection enhances the production of methane in two ways: (1) CO_2 enhances de-sorption of methane and (2) the injected CO_2 pushes methane towards the producer (CO_2 drive). In RECOPOL, the CO_2 adsorption was very slow, which likely enhanced the drive effect. An unexpected early breakthrough of CO_2 was observed in the RECOPOL pilot, which was likely caused by CO_2 overshooting the water in the cleats due to buoyancy. One of the key lessons learned from RECOPOL was that dewatering prior to CO_2 injection is necessary. Therefore, CBM has to precede the ECBM operation to effectively dewater the coal seam.

In the MOVECBM project, the RECOPOL site was continuously monitored and additional tests were conducted at the site to investigate what happened to the injected CO_2. For this purpose, the former injector was converted to a producer and part of the injected CO_2 was back-produced. Additional lab experiments were started to get some key information on swelling and adsorption to the coal. Also, a mini 4-spot pilot was conducted in the Velenje coalmine (Slovenia) to bridge the gap between lab and field scale. The mine injection pilot was used to test and link the coal-swelling model to the laboratory parameters. Shell's proprietary simulator MoReS was used with the swelling model of Bustin [6] and the RECOPOL pilot and additional MOVECBM tests were simulated again with the updated reservoir model. The aim was to better understand the long-term behavior of CO_2 in coal.

2. Adsorption model

The adsorption/desorption process is described by the extended Langmuir relation [7], in which the gas content is equal to:

$$G = (1 - w_a - w_m) \cdot V_{L,i} \frac{y_i \, p / p_{Li}}{1 + y_{CO2} \, p / p_{L,CO2} + y_{CH4} \, p / p_{L,CH4}} \quad \text{with } i = \text{CH}_4, \text{CO}_2 \qquad (1)$$

The extended Langmuir equation fits to experimental adsorption isotherms. The coal parameters from RECOPOL as obtained in the lab are, [8]: $p_{L,CH4}$ = 2.5 MPa, $p_{L,CO2}$ = 2.3 MPa, $V_{L,CH4}$ = 17 m^3/ton and $V_{L,CO2}$ = 87 m^3/ton. The average ash and moisture content are w_a=25% and w_m=5%, respectively. These parameters were determined on crushed coal. It was found that experiments on crushed coal tend to over-predict the gas storage capacity, because under in situ conditions not all sorption sites are accessible within reasonable time (i.e. project lifetime). To take this effect into account the two Langmuir volumes are multiplied by a factor 0.3. Figure 1 shows the corresponding isotherms based on the reduced Langmuir volumes. Note that the coal (lignite) from the Velenje mine has different characteristics (figure 2) : p_L =13.3 MPa, $V_{L,CH4}$ =18.6 m^3/ton and $V_{L,CO2}$ =74.7 m^3/ton.

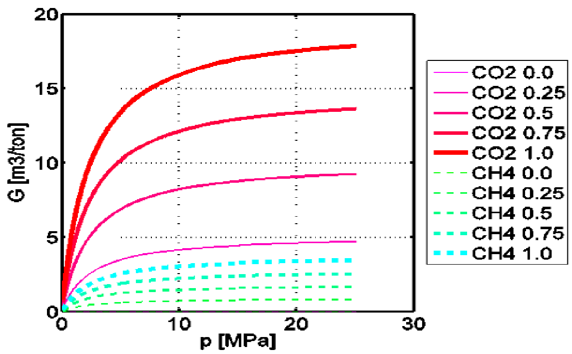

Figure 1. Gas storage capacity as a function of pressure and mol fraction in the gas phase (RECOPOL field test).

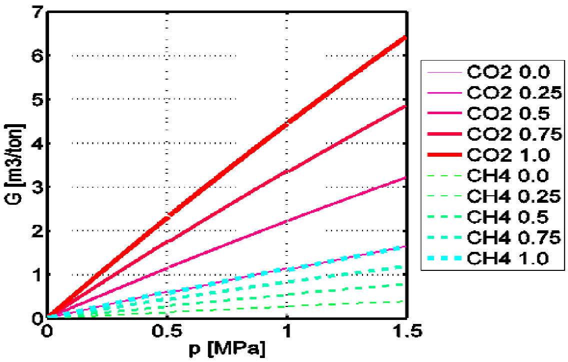

Figure 2. Gas storage capacity as a function of pressure and mol fraction in the gas phase (Velenje mine).

3. Coal swelling model

Coal swells, when it adsorbs CO_2 at reservoir pressures. This swelling can close cleats and decrease the coal permeability as the coal is subjected to a confining stress, such as the overburden stress. A consequence is that the

CO_2 well injectivity decreases. On the other hand, coal shrinks when methane and water are produced from it [9]. This shrinkage improves the permeability. Both effects are implemented in our reservoir model. Most swelling/shrinkage models are based on the Carmen-Kozeny equation for fractures:

$$k/k_0 = \exp\left(-3C_p \cdot \Delta\sigma_{eff}\right) \tag{2}$$

It relates a change in permeability k/k_0 to the effective compressive stress σ_{eff}, [Pa]. C_p [Pa^{-1}] is called the (average) pore compressibility constant. The suffix '0' refers to a reference condition. Essential assumptions behind this equation are:

1) The change in the porosity ϕ [-] is proportional with a change in the effective compressive stress σ_{eff}, or $\Delta\phi = -(1-\phi)/K\,\Delta\sigma_{eff}$.
2) The bulk matrix compressibility coefficient $1/K$ [Pa^{-1}] is proportional with the porosity, or $1/K = \phi\, C_p$.
3) The permeability k [m^2] relates to ϕ as $k \sim \phi^3/(1-\phi)^2$ or for low porosity as $k/k_0 = (\phi/\phi_0)^3$.

Experiments show that the permeability of coal exponentially depends on the effective stress over a substantial range of stress, like the Carmen-Kozeny equation predicts. Coal swelling models include that the porosity also changes by volumetric strain in the coal matrix following gas adsorption. Assuming that the vertical load or overburden stress is constant, this leads to the following equation [7]:

$$\varphi/\varphi_0 = \exp\left(C_p\left(\frac{1+\nu}{3(1-\nu)}(p-p_0) - \frac{2E}{9(1-\nu)}(\varepsilon_{ll}-\varepsilon_{ll0})\right)\right) \tag{3}$$

If the coal seam permeability is only controlled by horizontal stress, the above equation converts to [6, 10]

$$\varphi/\varphi_0 = \exp\left(C_p\left(\frac{\nu}{(1-\nu)}(p-p_0) - \frac{E}{3(1-\nu)}(\varepsilon_{ll}-\varepsilon_{ll0})\right)\right) \tag{4}$$

C_p is experimentally determined from a permeability change due to a change in the effective stress. E [Pa] and ν [-] are the Young modulus and the Poisson ratio, respectively. $\varepsilon_{ll} - \varepsilon_{ll0}$ is a change in the volumetric strain due to gas adsorption and can be related to the change in concentration of all the adsorbed gases n_s [mol/m^3]: $\varepsilon_{ll} - \varepsilon_{ll0} = \gamma(n_s - n_{s0})$. The constant γ [m^3/mol] is the ratio between the volumetric strain and the adsorbed concentration and has to be determined experimentally. We assume that γ has the same value for all gases. Note that n_s is proportional to the gas content G of the coal: n_s[mol/m^3] = 1000 G[m^3/kg] ρ_{coal} [kg/m^3] ρ_{gas}[kg/m^3] / M_{gas}[g/mol]. Typical experimental values found for coal and used in the simulation of the RECOPOL field test are: E = 4 GPa, ϕ_0 = 0.005, ν = 0.33, C_p = 0.2 MPa^{-1} and γ = 15 cc/mol.

Figure 3 shows the swelling model applied to the RECOPOL field. The cross shows the initial reservoir conditions. The dashed line shows the permeability change as a function of CH_4 desorption or adsorption (i.e. a

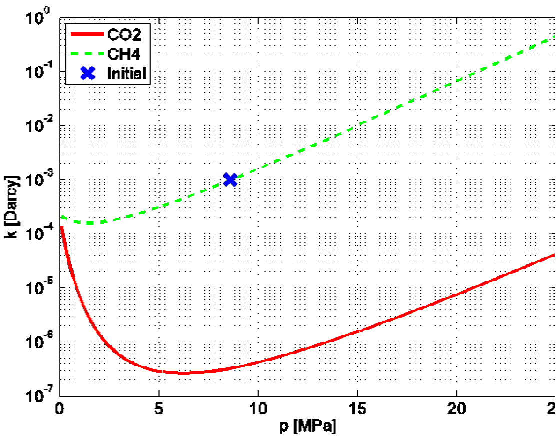

Figure 3. Permeability change as a function of pressure. (RECOPOL field test)

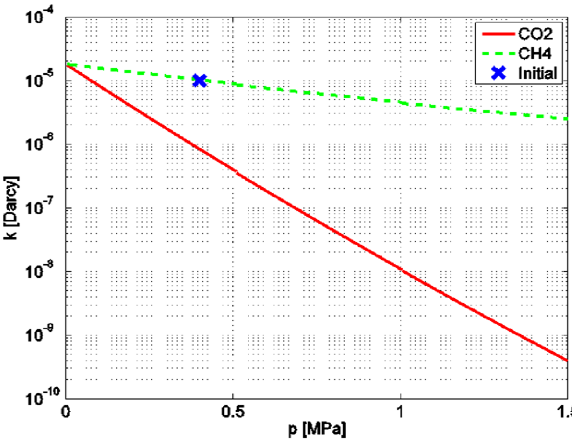

Figure 4. Permeability change as a function of pressure (Velenje mine)

function of pressure). The solid line shows the permeability reduction when all CH_4 is replaced by CO_2. It can be observed that the permeability can drop several orders of magnitudes, when CH_4 is replaced by CO_2.

Figure 4 shows the same plot for the Velenje mine experiment. Note that in the Velenje experiment pressures are much lower. In this range we are at the steep part of the Langmuir isotherm, thus sorption dominates the coal swelling. One can observe that the impact of swelling is extreme in the Velenje coal.

4. CO2 injection test in Velenje mine

One CO_2-injection well and three observation wells were drilled in the Velenje coalmine to study the behaviour of CO_2 in coal under in situ conditions. The wells were 30m long, cased up to 25m and fitted with plastic liners. The last 5m of the liners were perforated by 8 mm holes at 5 mm distance distributed in a spiral form. The effective diameter of each well was 90mm (including the liner). A total amount of 5.7 kg CO_2 was injected in the central injector during seven different pressure steps ranging from 1-12.5 barg. The pressure and production response was monitored in three observation wells, which were drilled 1m above, 3m left and 3m right from the injector (see figure 5).

The CO_2 injection was simulated with Shell's reservoir simulator MoReS. For this purpose, a radial grid was constructed consisting out of 20 grid blocks in the radial direction and 36 grid blocks in the z-direction. The grid was refined near the well and further refined near the injection interval. This refinement was necessary to correctly model the permeability reduction near the well bore due to swelling. The CO_2 in the well bore was also modeled by including the well bore and casing in the grid (figure 5). A no flow boundary was applied near the mineshaft and two pressure boundaries were applied to the far field (30m from well) both were set to 3 barg, which is equal to the backpressure from the coal-formation observed in the observation wells.

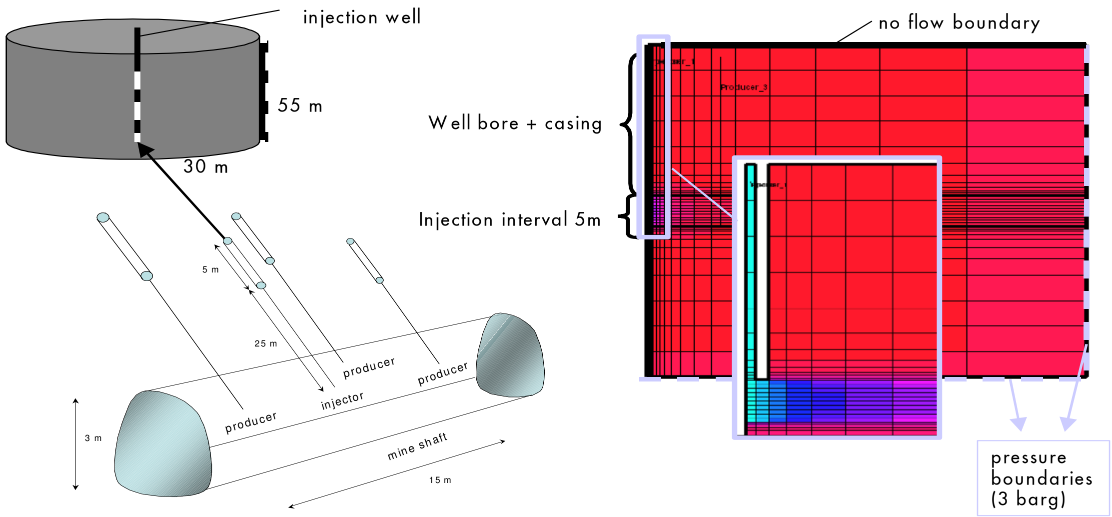

Figure 5. Schematic of mine experiment and simulation grid

The CO_2 mass-flow into the well was matched to the historic mass-flow of the mine experiment. The corresponding pressure build-up and fall-off were simulated. The permeability was adjusted to match these pressure responses. The following parameters were used for the swelling model: E = 5 GPa, ϕ_0 = 0.01, ν = 0.3, C_p = 0.3 MPa^{-1}, k_0 = 0.01 mD and γ = 22 cc/mol. Simulations were also conducted without a swelling and compaction model. A reasonable agreement was found between the simulation with swelling and the experiment (figure 6). The pressure steps could be reproduced and the pressure fall-offs have the same magnitude. However, the shapes of the pressure fall-offs differ. If no swelling model is applied, the pressure fall-off is much faster and the curves cannot be matched at all.

Coal swelling reduced the permeability significantly sealing the well and leaving a pressure of 12 barg on the injector after the experiment. However, weeks after the experiment improved pressure communication between the injector and observation wells was observed indicating that CO_2 injection had created new fractures in the coal. There are several possible explanations for the formation of these fractures: The CO_2 had dried the coal causing cracks or the stress caused by the adsorption of CO_2 lead to fractures.

The swelling model of Bustin [6] was successfully applied using typical experimental values for coal giving us confidence in the modeling In this sense, the mine experiment allowed us to bridge the gap between field pilot and lab experiment.

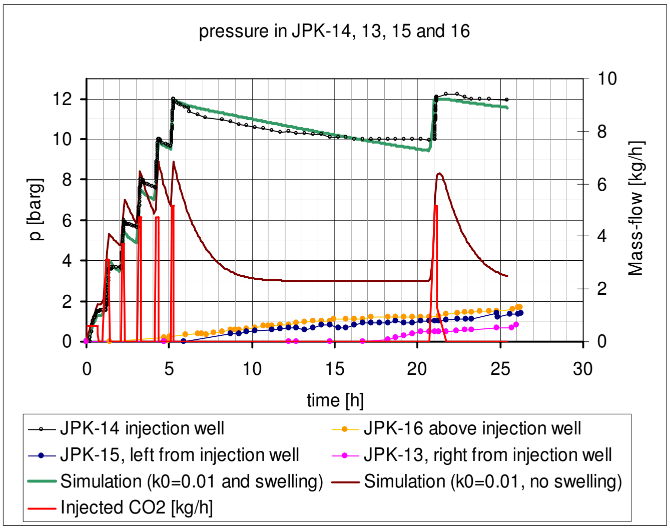

Figure 6. Pressures of wells (simulation and experiment) and CO_2 injection rate.

5. Two well ECBM-pilot in Poland

5.1. Location, and reservoir model

The RECOPOL test site is located in the west central Upper Silesian basin in the South of Poland (figure 7) near the Czech border and falls under the concession area of a Silesian mine. The pilot area consists of a small fault-block, which has a triangular shape. The two faults are expected to be sealing. The deposits in the block dip 12° to the north and consist of alternating layers of sandstone, clay and coal, [11]. Permeability is relatively low, in the range of 0.5 to 2 mD. The reservoir is located at a depth of 1000m.

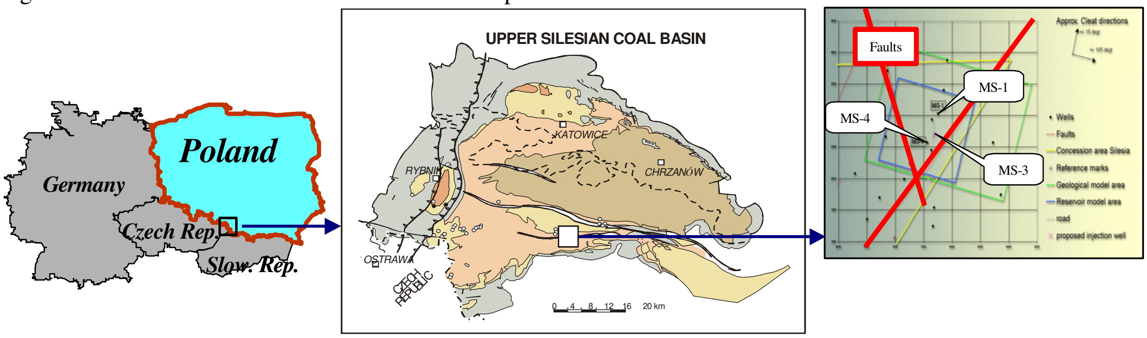

Figure 7. Location of ECBM pilot in Poland

On the test site, there were two old CBM pilot-wells, MS-1 and MS-4 (up-dip), spaced 375m apart. A pump was installed at the producer MS-4. The old well MS-1 was not used. A new injection well, MS-3 was drilled in between MS-1 and MS-4. CO_2 was injected in MS-3. There are indications that CO_2 only entered the top coal layer 364, which is 3m thick, [5]. Initially, injection rates were low, possibly because the injector (MS-3) was impaired. A successful frac-job of MS-3 was completed in April 2005, which resolved the injectivity problems.

A reservoir model (figure 8) was constructed, which represents a triangular area of 1.35 km^2. The CO_2 injection and production in one coal seam (364) was modeled. Note that the grid refinement near the top of the coal seam is necessary to correctly model the gravity override of CO_2 and predict the correct breakthrough time of CO_2. Also, a refined grid near the wells is necessary to correctly predict the impact of swelling on injection/production. Coal swelling was included in the model. The initial coal porosity was 0.5%. and the initial gas content was assumed to be 3 m^3/ton.

Because matrix permeability is very low, there is no matrix/matrix transport. Therefore, a single porosity model proved to be sufficient. In the previous study [5], a dual porosity model was used, but similar results could be obtained with a single porosity model, which reduces the total number of grid blocks by a factor of 2. Coal is modeled as a component in the solid phase. The components CH_4 and CO_2 can be both in the solid phase (adsorbed) and in the gas phase. The transfer is controlled by desorption and adsorption reactions, which in their equilibrium convert to the extended Langmuir equation. The kinetics of the reactions determine the sorption rates and are based on methane desorption from coal cores. Note that lab experiments showed that sorption rates on powders are much faster and are not representative for the field. It was found that sorption slows down significantly, when grain size increases [12].

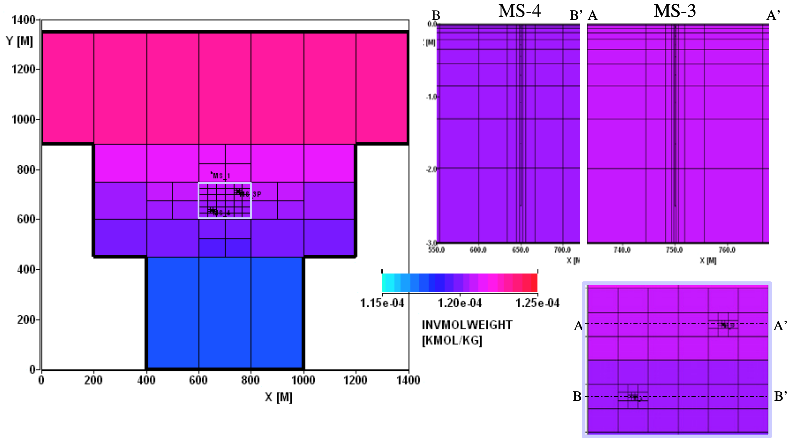

Figure 8. Simulation grid: contours show initial CH_4 concentration

5.2. Results

The CO_2-injection rates of the simulation were matched to the field rates. The corresponding bottom hole pressures (BHPs) of the field test and the simulation matched in the period after the frac-job. In order to match the BHPs in the period prior to the frac-job a skin effect was applied around the injector. The permeability in an area 3m around the injector was reduced by a factor 500. This skin effect was removed after the frac-job. The frac-data indicated that the frac-job had opened the cleats around the well bore. There were indications (the very slow pressure fall-off) that the cleats, which were opened by the frac-job, closed again after the CO_2-injection was stopped. To model this effect the skin effect was re-applied after the CO_2 injection. Figure 9 compares the CO_2-injection rates and corresponding BHPs. It can be observed that a good match was obtained. The skin effect around the injector together with the permeability reduction due to swelling could explain the initial low injection rates and slow pressure fall-off after the experiment.

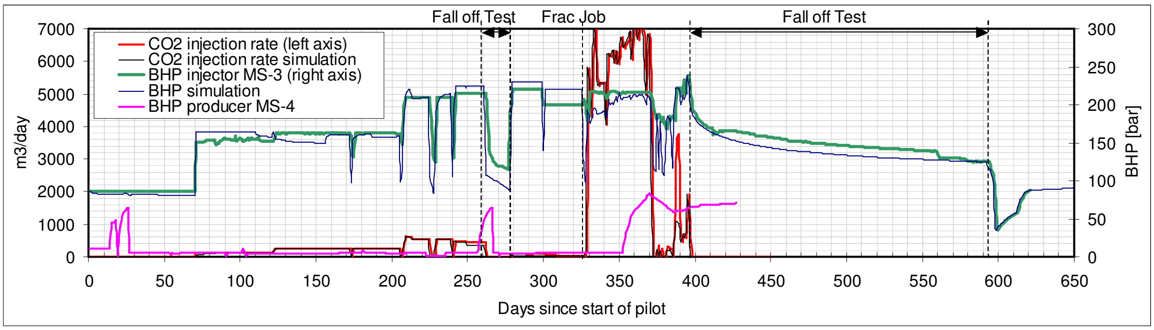

Figure 9. CO_2 injection rate and pressure (MS-3); comparison between simulation model and field.

The response of the CO_2-injection on the methane production was observed in the producer MS-4. The BHP from the producer was derived from the water level in the well. In the simulation, this derived BHP was used as a pressure constraint for the producer. Two simulations were conducted: 1) without any CO_2 injection to determine the CBM baseline 2) with the CO_2 injection matched to the field rates.

Figure 10 shows the production response of the field and the simulations. It can be observed that the response of the simulation is close to the field data. The methane production is clearly enhanced with respect to the CBM baseline, but CO_2 starts to break through very early in the producer too. Field rates are close to the simulated rates. The massive breakthrough of CO_2 after the frac-job and significant methane enhancement can also be observed in the model. The early breakthrough can be explained by the gravity override of the CO_2 in the cleats. Note that to model this effect sufficient grid blocks need to be used in the z-direction, especially in the vicinity of the cap-rock. Vertical grid spacing was typically on cm scale near the cap-rock.

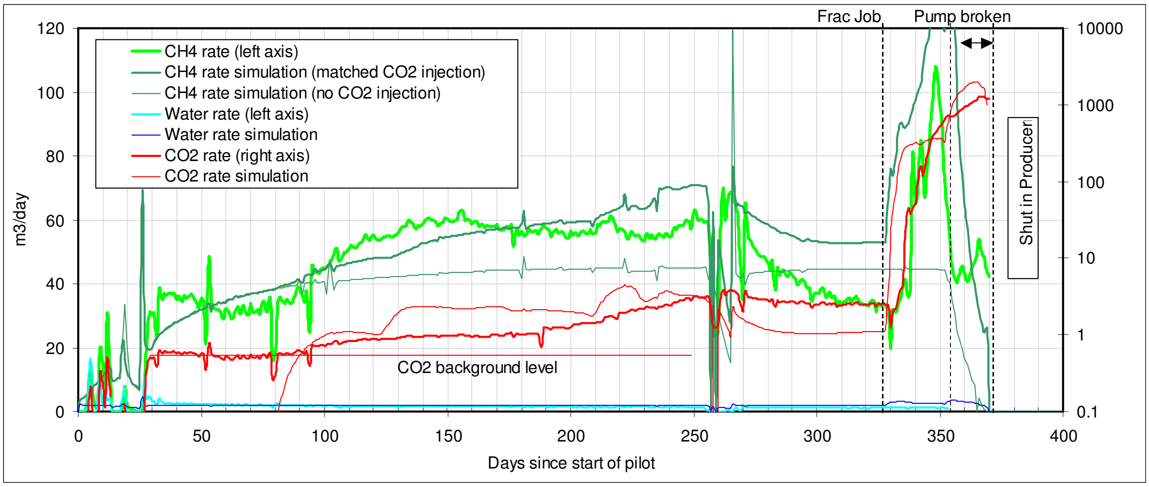

Figure 10. Water, CO_2 and CH_4 production (MS-4); a comparison between field data and simulation response.

At the end of the pilot (1000 days) the injector MS-3 was back-produced for 100 days, see for details [13]. Very small water rates of 0.01-0.1 m^3/day were observed in the field, while the gas production was in the order of 60 m^3/day with 70% CO_2 and 30% CH_4 initially. At the end of the field test, the composition had shifted towards 40% CO_2 and 60% CH_4. The simulation could explain the small water production. However, smaller water and gas production rates were observed in the simulation: 0.0001 m^3/day and 10 m^3/day, respectively. It turned out (figure 11) that all the water around the well bore was swept away by the CO_2 and the reduced permeability caused by the coal swelling prevented the water to flow back. The initial CO_2 concentration in the simulation was close to 100% indicating a perfect sweep.

The simulation probably over-predicted the CO_2 adsorption around the well bore. This also increased the amount of coal swelling, which explains the lower water and gas rates in the simulation. Possible explanations for the lower CO_2 and higher CH_4 concentrations observed in the field are: 1) an imperfect sweep, 2) a slower adsorption of CO_2 (kinetic effect) or 3) a contribution from other coal seams. These possibilities will be further investigated.

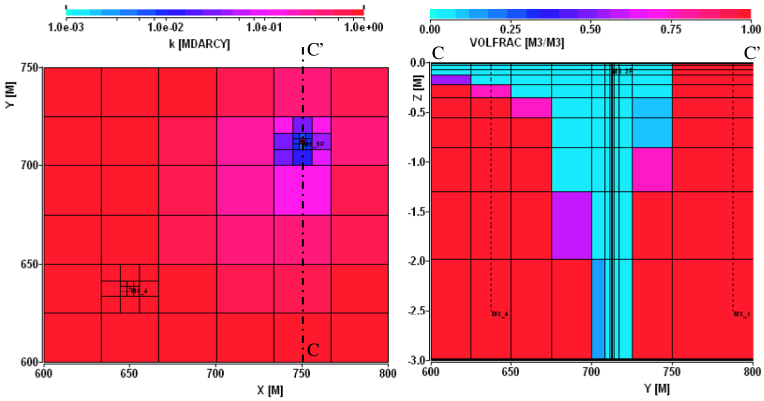

Figure 11. Permeability (left) and water saturation (right) at end of the project

6. Conclusions

The swelling model based on typical experimental values allowed us to better understand results of the ECBM field test in Poland and the mine experiment in Slovenia. The kinetic effect of adsorption is included in the swelling model, because it is directly linked to the adsorbed gases in the simulator.

A reasonable history match of the ECBM field pilot was obtained for the main production part of the pilot. However, still some differences exist between the simulation and second part of the pilot, i.e. the production of the former injection MS-3. A very low water production was observed in both simulation and field experiment, but the concentration of the back-produced gas was almost 100% CO_2 in the simulation, while in the field the CO_2 concentration was 70% gradually declining towards 40%. Possible reasons for the differences are:

1. Part of the coal was not accessed by the CO_2 due to imperfect sweep efficiency.
2. Slower kinetics of the sorption reactions causing a slower CO_2 adsorption and methane desorption.

The low water production observed in the back-production of the former injector could be explained by an effective CO_2 sweep that carried away the water during the injection. Furthermore, the reduced permeability caused by coal swelling prevented the water to flow back towards the injector.

The CO_2 injection test in the Velenje coalmine could be adequately simulated with Shell's simulator MoReS. The permeability reduction was successfully modeled with the swelling model of Bustin [6]. However, the improved pressure communication between the wells, which was observed weeks later, could not be modeled. The modeling of this effect will require the coupling of a geo-mechanical simulator and reservoir simulator, because the creation of fractures depends on the stress fields.

The accessibility of a coal seam can be impaired by coal swelling, which can lead to injection problems. If these problems can be overcome, coal is in principle an attractive storage medium for CO_2. CO_2 adsorbs strongly to the coal locking it firmly in place. Moreover, coal swelling reduces the permeability of a coal seam, which can improve its long-term 'sealing' properties.

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