

COAL-MATRIX SWELLING BY CO₂ ADSORPTION AND A MODEL OF PERMEABILITY REDUCTION

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ABSTRACT CO₂ gas adsorption phenomena is important to carry CO₂-Enhanced Coal Bed Methane Recovery (CO₂-ECBMR) in coal seams, since the adsorption induce coal-matrix swelling and permeability reduction. The pilot test on CO₂ Enhanced Coal Bed Methane Recovery (CO₂ -ECBMR) was carried out at Yubari City, Hokkaido, Japan during 2002 to 2007. A targeted coal seam at the project was located about 890m below the surface. The project had a problem on CO₂ injection with low injection rate of about 3ton/day and reduction of CO₂ injection rate during 3 to 10 days from the start of the injection. In the pilot-test data, it was observed as a similar decreasing pattern in time curves of CO₂ injection rate was found. In this study, an analytical radial flow model for coal seams has been proposed to evaluate CO₂ swelling ratio (β) that is the ratio of permeability reduction of the coal seam by coal matrix swelling in CO₂ saturated zone based on the assumptions that the coal seam zone is open at its outer boundary, CO₂ and water saturated zones are separated without mixing each other and the diameter of CO₂ saturated zone is expanding to cumulative injection CO₂. The injection rates of Yubari ECBM pilot test has been analyzed with the presented flow model. The time curves of the injection rate at the Yubari ECBMR pilot test were roughly simulated by matching with parameters of original permeability, swelling factor and diameter of the coal seam with open boundary. The swelling ratio on permeability has been evaluated as $\beta = 1/50$ to $1/23$ and original coal permeability $k_w \approx 3$ md by matching with monitoring data measured.

Keywords: coal seam, coal bed methane gas, CO₂, permeability, reduction, swelling

1 INTRODUCTION

CO₂ capture and storage (CCS) is one of expected methods to reduce its emissions into the atmosphere. There are various underground reservoirs and layers for the storages. For example, aquifer, drained oil and gas reservoirs and unmined coal seams. The coal seams have feasibility because coal can adsorb CO₂ gas volume which is almost double of methane (Law et al., 2002). However, there is a problem that coal matrix swells by adsorbing CO₂ and reduces its permeability as reported by Palmer and J. Mansoori (1998).

The Japan consortium to enhance CO₂ sequestrations into coal seams carried out the project on CO₂ sequestration into coal seams at Yubari City, Hokkaido (2). A targeted coal seam at Yubari is located about 890m below the surface. Figure 1 shows the targeted coal seam and

locations of a CO₂ injector and gas and a water producer at Yubari ECBM pilot-test. The principal target for CO₂ injection was the Yubari Lower Seam between -890 to 896 that is included in the area 1 km × 1.5 km. The mudstone ≈ 500m in thickness is capable of sealing the gases. The effective coal seam thickness is around 5m. The CO₂ injector (IW-1) was drilled at the location in 2004 as shown in Figure 1, and the well test analysis and CO₂ injection and production tests with Huff-Puff were done. The absolute horizontal permeability was evaluated as 1 md by the fall-off test.

Furthermore, the fluids producer was drilled at the position located 67 m from the injector in 2005, and the pilot test using two wells was started from 2005 and the injectivity was improved. The major pilot tests of ECBMR using two wells were carried out by continuous CO₂ injection and water and gas productions from 2006. The two wells were drilled

at the location near the bottom impermeable boundary terminated by Kashima#3 Fault (Yamaguchi et al., 2007).

Liquid CO₂ was injected due to heat loss along the deep injection tubing to relatively low temperature sediments (8 to 29 °C) (Yasunami et al., 2010). The absolute pressure and temperature at the bottom hole was approximately 15.5MPa and 28°C.

Replacements of usual tubing with thermal insulated tubing including argon gas layer were carried out, however, the temperature at the bottom hole was lower than the CO₂ critical temperature. In order to increase CO₂ injection rate into coal seams, supercritical CO₂ condition, thermal insulated tubings and a heater were used, however it was not able to increase the injection rate, because of large heat loss and coal swelling effects due to CO₂ adsorption in the coal seam. The CO₂ permeability of coal cores drilled from Yubari Lower seam was measured by Sasaki and Fujii (2002) against the three-dimensional stress, and the coal matrix swelling of the core was observed in liquid CO₂ (Fujii et al., 2007). Pulmer and Mansoori (1998) have presented the swell model for numerical simulation by giving permeability change from CO₂ saturation.

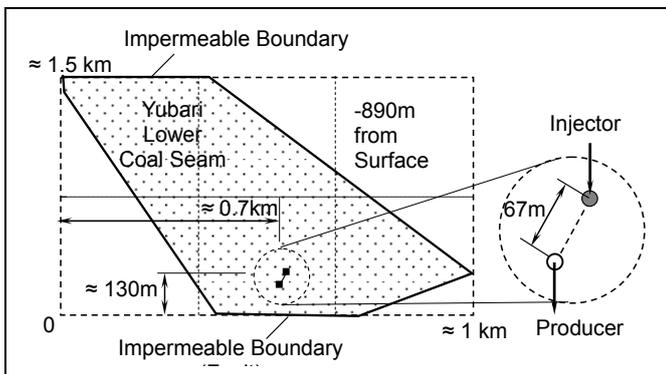


Figure 1. Schematic figure showing targeted coal seam and locations of a CO₂ injector and a producer at Yubari ECBM pilot-test

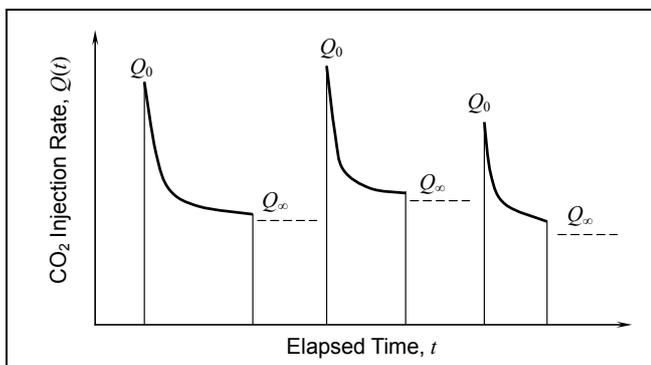


Figure 2. Schematic decay pattern of CO₂ injection rate observed at Yubari ECBM pilot-test

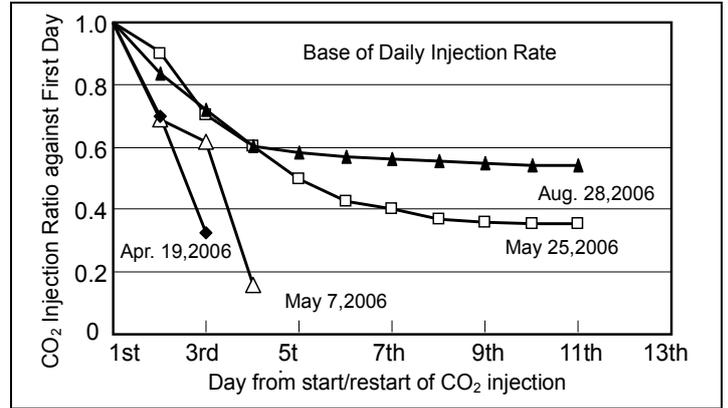


Figure 3. Decay ratio of daily CO₂ injection rate monitored at Yubari ECBM-pilot test

Furthermore, the CO₂ injection rate for each tests carried in the projects during 2006 and 2007, was decreased against time after each start of runs with showing a similar decay pattern. Figure 2 shows the schematic decay patterns of CO₂ injection rate observed at Yubari ECBM pilot-test field. Figure 3 shows the ratio of the daily CO₂ injection rate monitored at Yubari ECBM pilot-test field, based on the rate in first day for each tests. In the first run done on April 2006, the decay ratio of injection rate is obviously larger than that of later tests as shown in Figure 3. It was concluded that the coal swelling effect by adsorbing CO₂ on the injection rate was becoming smaller with number cycles of injection and release CO₂ by pressure reduction.

2 RADIAL FLOW MODELING

2.1 Targeted range for CO₂ injection rate

Assume a 250 to 500 MW electrical power station using fossil fuel, the CO₂ generating rate is roughly estimated as 50 kg/s (≈4,300 ton/day). Thus, the injection mass rate into a coal seam using a vertical well is economically expected to be order of 1 kg/s or 100 t/day per injection well.

2.2 Two fill-up regions with CO₂ and water

In this modeling, an independent area of the coal seam for ECBMR is assumed to be d_{∞} (m) in diameter and h (m) in thickness. It was assumed that that a coal seam is saturated with water and methane gas is adsorbed following CH₄ Langmuir volume, v_L (std-m³/t) and CH₄ Langmuir pressure, P_L (MPa), and when CO₂ is injected into the coal seam from a injector the cylindrical area around the injector is filled and saturated with CO₂. The cylindrical zone is expanding with total CO₂ injection amount which is equal to volume of cumulative CO₂ from the start of injection.

The water and CO₂ saturated zones are assume to be separated with the boundary d_c (m) in diameter ideally without any mixing CO₂ and water. Thus life of the targeted coal seam for ECBMR is defined by the time to saturate porous-space and adsorption capacity of the coal seam with injected with CO₂. Assume Q (kg/s) is CO₂ mass injection rate from the injector that is function of time t (s), diameter d_c of the CO₂ saturated zone is ideally given against the cumulative injection CO₂ as,

$$d_c = \left(\frac{4}{\rho_C \phi_C h \pi} \int_0^t Q(t) dt + d_{w0}^2 \right)^{\frac{1}{2}} \quad (1)$$

where ρ_C (kg/m³) is CO₂ density, d_{w0} (m) is the diameter of injection casing filled with CO₂ at $t = 0$, and ϕ_C is total of physical porosity, ϕ_∞ , and equivalent porosity, ϕ_e of coal as

$$\phi_C = \phi_\infty + \phi_e \quad (2)$$

In the model, ϕ_e is evaluated from the adsorption capacity m_a (kg/m³) and CO₂ density ρ_C (kg/m³) against coal seam temperature and pressure.

$$\phi_e = \frac{m_a}{\rho_C} \quad (3)$$

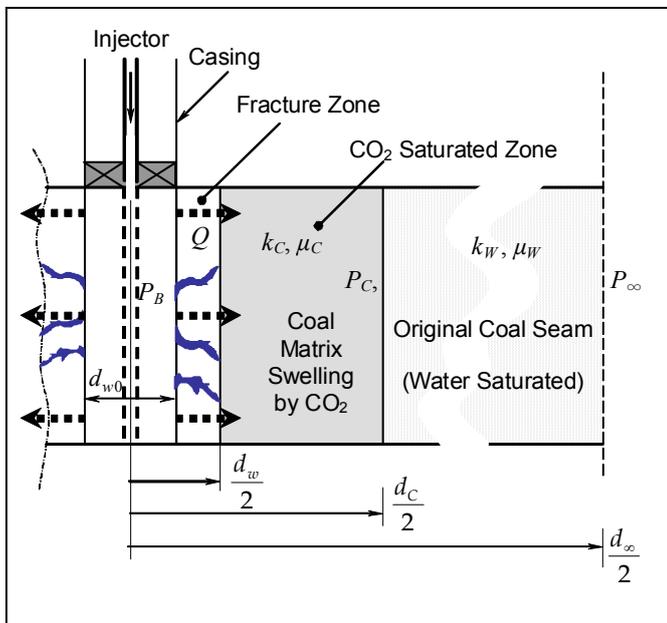


Figure 4. Schematic figure showing the radial flow model for CO₂ injection into coal seams (Cross section view)

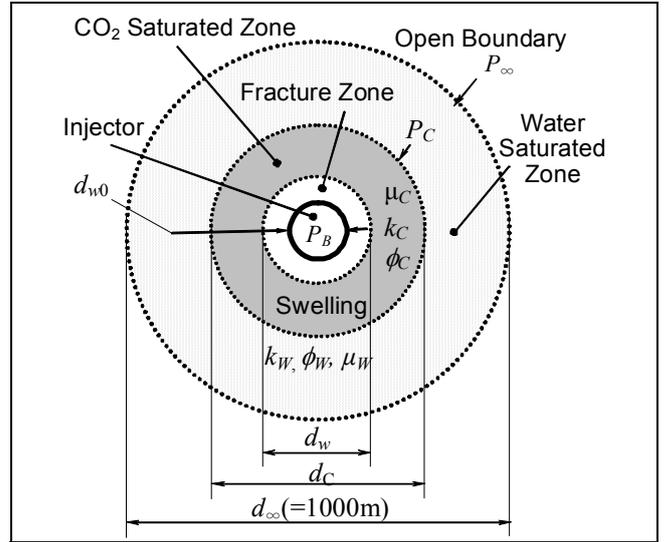


Figure 5. Radial flow model of CO₂ injection into coal seam (Plan view)

2.3 Predicting injection rate considering permeability change with swelling ratio

The initial horizontal permeability of the coal seam and reduced permeability after coal matrix swelling are defined with k_W (m² or md) and k_C (m² or md), respectively. In practice, the injection fluid may be changed gradually from water to supercritical CO₂ during a radian band. However, it is assumed that in the zone of $r \leq d_c/2$, permeability k_C immediately reduces from the original permeability k_W by coal matrix swelling as,

$$k_C = \beta \cdot k_W \quad (4)$$

where β (-) is permeability reduction ratio by coal matrix swelling that is hereinafter called swelling ratio. In present model, permeability of the fractured zone around the injector is assumed to be much higher than the initial coal seam, and the actual injector's diameter may be replaced with the diameter of the fractured zone. Let assume P_B (Pa) is bottom hole pressure at the injector, P_C (Pa) is the pressure at the boundary between two zones, and P_∞ (Pa) is the pressure at the open boundary of the independent area of coal seam, the pressure reduction against radial flows in both of CO₂ and water saturated zones can be given by following Darcy's law in cylindrical coordinate (Yasunami et al., 2010)

$$P_B - P_C = \frac{\mu_C}{2\pi k_C h} \cdot \ln\left(\frac{d_C}{d_w}\right) \cdot Q(t) \quad (5)$$

$$P_C - P_\infty = \frac{\mu_W}{2\pi k_W h} \cdot \ln\left(\frac{d_\infty}{d_C}\right) \cdot Q(t) \quad (6)$$

where d_w is evaluated diameter that shows the high permeability zone around the injector, μ_C (Pas) is CO₂ viscosity, μ_w (Pas) is water viscosity. For example, the viscosity ratio is evaluated as $\mu_C/\mu_w \approx 0.1$ for supercritical CO₂ condition.

From equations (4) to (6), the flow rate Q can be assembled as follows

$$Q(t) = \frac{2\pi\rho_C \cdot k_w h\beta(P_B - P_\infty)}{\mu_C \cdot \ln\left(\frac{d_C}{d_w}\right) + \beta\mu_w \cdot \ln\left(\frac{d_\infty}{d_C}\right)} \quad (7)$$

Transmissibility is usually defined including the fluid viscosity and density, however the transmissibility for the initial coal seam is given as $T = hk_w$ (m³) in this study, because the system includes two kinds of fluids in the seam.

Furthermore, initial CO₂ injection rate, $Q_0 = Q(0)$, and steady state CO₂ injection rate, $Q_\infty = Q(\infty)$, are expressed by following equations;

$$Q_0 = Q(0) = \frac{2\pi\rho_C \cdot k_w h(P_B - P_\infty)}{\mu_w \ln\left(\frac{d_\infty}{d_w}\right)} \quad (8)$$

$$Q_\infty = Q(\infty) = \frac{2\pi\rho_C \cdot k_w h\beta(P_B - P_\infty)}{\mu_C \ln\left(\frac{d_\infty}{d_w}\right)} \quad (9)$$

Therefore, the value of called swelling ratio β can be evaluated from the ratio, Q_∞/Q_0 , times the viscosity ratio, μ_C/μ_w , as;

$$\beta = \frac{Q_\infty}{Q_0} \cdot \frac{\mu_C}{\mu_w} \quad (10)$$

2.4 Numerical calculation procedure

The analytical simulation has been carried out by following calculation process with time step, $\Delta t = t - t'$ (s); (t is present time; t' is the time on previous calculation step).

- Set coal seam conditions; $h, T_\infty, P_\infty, d_\infty, k_w, \mu_w, \mu_C, \beta$ and P_B at $t = t' = 0$.
- Calculate CO₂ density ρ_C for T_∞ and P_B using with the software; PROPASS.
- Calculate the initial CO₂ injection rate, $Q_0 = Q(0)$ at $t = 0$ by Eq. (8).
- Set time forward by $t = t' + \Delta t$.
- Calculate cumulative CO₂ injection amount $\Sigma Q\Delta t$ from $t = 0$, and evaluate diameter d_C (m) by Eq. (1).
- Calculate $Q(t)$ from Eq.(7) and set $t' = t$

- Return to (d) and Circulate process from (d) and (f) until getting flow rate $Q(t)$ close to the steady state flow Q_∞ .

For the calculations to simulate the tests at Yubari ECBM pilot-test, following values were used.

- Height of coal seam; $h = 5$ m
- Coal matrix porosity; $\phi_o = 0.01$ (see Yamaguchi et al., 2007)
- CO₂ adsorption; $m_a = 66$ kg/m³ (see Nako and Fujioka, 2007)
- CO₂ density; $\rho_C = 860$ kg/m³
- Initial temperature of coal seams; $T_\infty = 30$ °C (see Yasunami et al., 2010)
- Pressure at open boundary; $P_\infty = 10.2$ MPa
- CO₂ injection pressure (BHP); $P_B = 15.0$ MPa
- Diameter of fractured zone around CO₂ injector, $d_w = 1$ to 2 m

On the other hand, values of parameters; d_∞, k_w and β were evaluated with calculations matching with monitored results at Yubari ECBM pilot-test.

3 CALCULATION RESULTS FOR EVALUATION OF MODEL PARAMETERS

3.1 Matching procedure with monitoring data

Figure 6 shows a sensitivity of initial horizontal permeability k_w on CO₂ injection rate time curve by matching with monitored value at Yubari ECBM pilot-test. It is clear that the original permeability from August 28 to September 6, 2006 can be evaluated as $k_w \approx 3$ md based on initial injection rate Q_0 , and $\beta = 1/50$ has a good matching with Q_∞ . Figure 7 also show the sensitivity of diameter d_∞ of the independent coal seam on the same CO₂ injection rate time curve. The results are not so much sensible to d_∞ . Thus, $d_\infty = 1000$ m was used for other calculations.

Figure 8 shows sensitivity of swelling ratio β of coal seam on CO₂ injection rate for Yubari pilot test from July 19 to 28, 2007. The case of 2007, the swelling ratio on permeability is smaller than that of 2006.

Based on above calculations to get matching with the monitored data, the parameters of $k_w = 2.8$, $\beta = 1/50$ and $d_\infty = 1000$ m have been evaluated for Yubari ECBM pilot-test from August 28 to September 6, 2006. Other values of the parameters have been evaluated with same procedures matching with the monitored values at Yubari ECBM pilot-test.

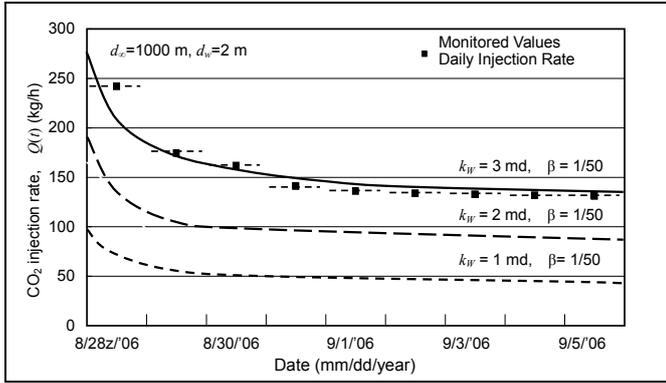


Figure 6. Sensitivity of original permeability, k_W on CO_2 injection rate monitored at Yubari pilot test from August 28 to September 6, 2006.

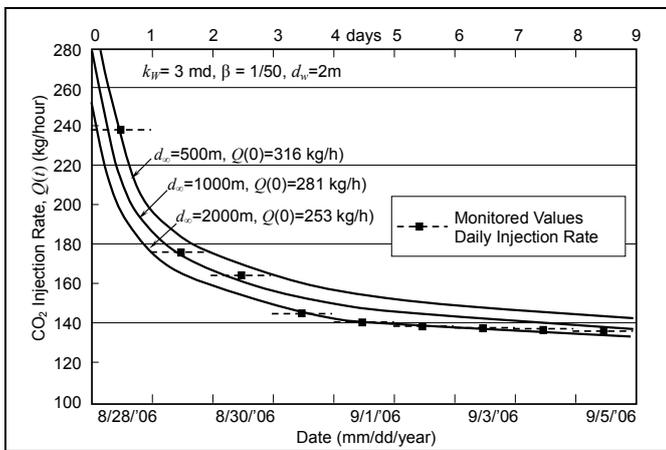


Figure 7. Sensitivity of diameter d_∞ of the independent coal seam on CO_2 injection rate for Yubari pilot test from August 28 to September 6, 2006

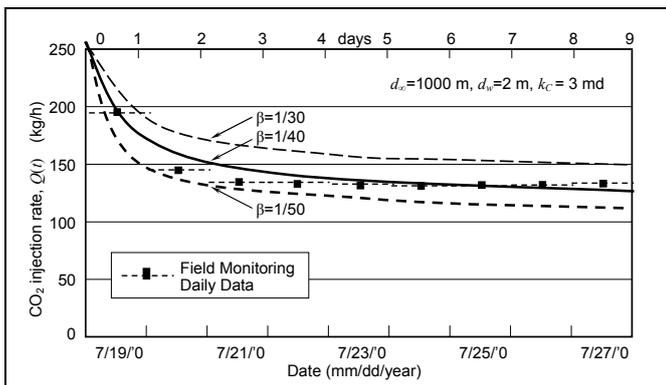


Figure 8. Sensitivity of swelling ratio β of coal seam on CO_2 injection rate monitored at Yubari pilot test from July 19 to 28, 2007

3.2 Evaluated original permeability and swelling ratio

Figure 9 shows changing swelling ratio β and original permeability k_W at start of each injection test against date during April, 2006 to November, 2007 except winter time when the pilot test site was closed. The swelling ratio and original permeability were evaluate as,

$$\beta = \frac{1}{50} \text{ to } \frac{1}{23} ; k_W \cong 3 \text{ md} \quad (11)$$

During May 10th to 19th, 2006, N_2 had been injected to reset the coal matrix swelling, then CO_2 injection rate was returned to one as $k_C \approx 3 \text{ md}$ as same as the original permeability $k_W \approx 3 \text{ md}$ during few days after restarting CO_2 injection, however the coal matrix swelling was again observed after restart of CO_2 injection. The swelling ratio shows a trend increasing with date in 2006, and became $\beta=1/23$ before shut in the wells in the winter. In the spring, 2007, the swelling ratio was evaluated as $\beta=1/30$ that is little smaller than that of the last value in 2006. The reason may be that in the winter CO_2 diffused and adsorbed in the saturated area, then increased the coal matrix swelling. The original permeability was measured as around 1 md by the fall-off test in 2004, however it was expected that the permeability was returned to the original value after some of continuous injection tests due to changing the injector's skin factor by fracturing coal matrix around the injector.

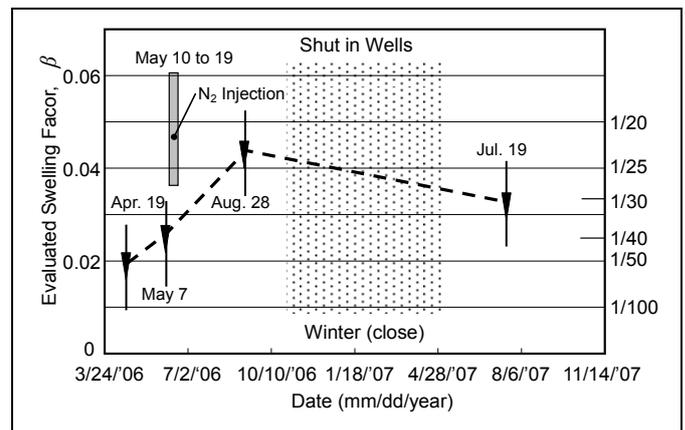


Figure 9. Evaluated swelling ratio β for each injection test at Yubari pilot test from April, 2006 to July, 2007

4 CONCLUSION

The Yubari ECBM pilot test had a problem of low CO_2 injection rate of about 3ton/day that is 1/10 of the predicted value and the CO_2 injection rate was decreased during 3 to 10 days after starting CO_2

injection due to permeability reduction. The reason was expected by coal matrix swelling in the coal seam around the injector by adsorption of CO₂. A similar decreasing pattern in the time curves of CO₂ injection rate was found, because of decreasing permeability around the injector due to the coal matrix swelling.

In this paper, an analytical radial flow model for coal seams has been proposed to evaluate CO₂ swelling ratio (β) that is the ratio of permeability reduction of the coal seam by coal matrix swelling in CO₂-saturated zone based on the assumptions that the coal seam zone is open at its outer boundary, CO₂ and water saturated zones are separated without mixing each other and the diameter of CO₂ saturated zone is expanding to cumulative injection CO₂.

The injection rates of Yubari ECBM pilot test has been analyzed with the presented flow model. The time curves of the injection rate at the Yubari ECBMR pilot test were roughly simulated by matching with parameters of original permeability, swelling factor and diameter of the coal seam with open boundary. The swelling ratio on permeability has been evaluated as $\beta = 1/50$ to $1/23$ and original coal permeability $k_w \approx 3$ md by matching with monitoring data measured.

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