# COAL-MATRIX SWELLING BY $CO_2$ ADSORPTION AND A MODEL OF PERMEABILITY REDUCTION

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**ABSTRACT** $CO_2$ gas adsorption phenomena is important to carry $CO_2$-Enhanced Coal Bed Methane Recovery($CO_2$-ECBMR) in coal seams, since the adsorption induce coal-matrix swelling and permeability reduction. The pilot test on $CO_2$ Enhanced Coal Bed Methane Recovery ($CO_2$ -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 $CO_2$ injection with low injection rate of about 3ton/day and reduction of $CO_2$ 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 $CO_2$ injection rate was found. In this study, an analytical radial flow model for coal seams has been proposed to evaluate $CO_2$ swelling ratio ($\beta$) that is the ratio of permeability reduction of the coal seam by coal matrix swelling in $CO_2$ saturated zone based on the assumptions that the coal seam zone is open at its outer boundary, $CO_2$ and water saturated zones are separated without mixing each other and the diameter of $CO_2$ saturated zone is expanding to cumulative injection $CO_2$. 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, $CO_2$, permeability, reduction, swelling

## 1 INTRODUCTION

$CO_2$ 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 $CO_2$ gas volume which is almost double of methane (Law et al., 2002). However, there is a problem that coal matrix swells by adsorbing $CO_2$ and reduces its permeability as reported by Palmer and J. Mansoori (1998).

The Japan consortium to enhance $CO_2$ sequestrations into coal seams carried out the project on $CO_2$ 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 $CO_2$ injector and gas and a water producer at Yubari ECBM pilot-test. The principal target for $CO_2$ 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 $CO_2$ injector (IW-1) was drilled at the location in 2004 as shown in Figure 1, and the well test analysis and $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 28ºC.

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 $CO_2$ critical temperature. In order to increase $CO_2$ injection rate into coal seams, supercritical $CO_2$ 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 $CO_2$ adsorption in the coal seam. The $CO_2$ 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 $CO_2$ (Fujii et al., 2007). Pulmer and Mansoori (1998) have presented the swell model for numerical simulation by giving permeability change from $CO_2$ saturation.

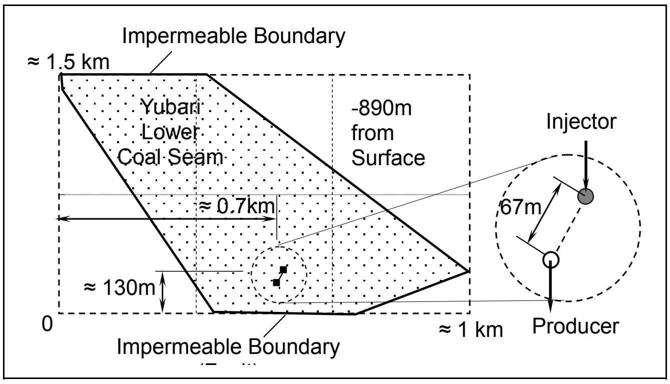

Figure 1. Schematic figure showing targeted coal seam and locations of a $CO_2$ injector and a producer at Yubari ECBM pilot-test

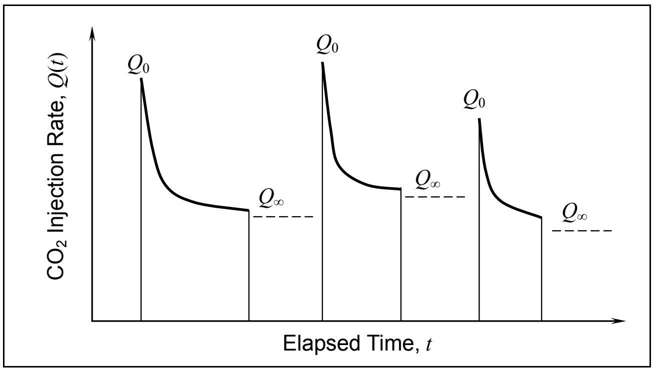

Figure 2. Schematic decay pattern of $CO_2$ injection rate observed at Yubari ECBM pilot-test

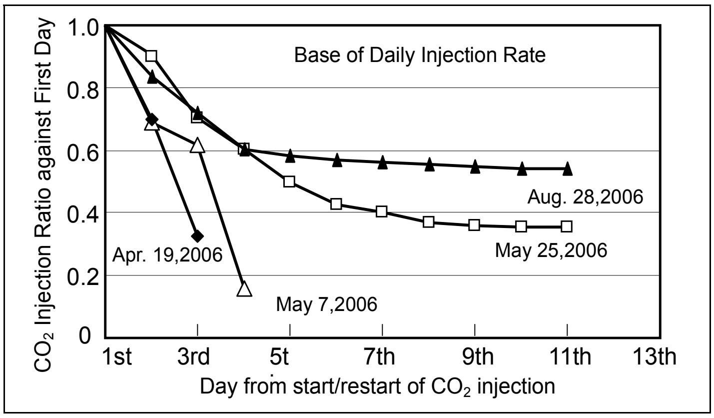

Figure 3. Decay ratio of daily $CO_2$ injection rate monitored at Yubari ECBM-pilot test

Furthermore, the $CO_2$ 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 $CO_2$ injection rate observed at Yubari ECBM pilot-test field. Figure 3 shows the ratio of the daily $CO_2$ 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 $CO_2$ on the injection rate was becoming smaller with number cycles of injection and release $CO_2$ by pressure reduction.

## 2 RADİAL FLOW MODELİNG

### 2.1 Targeted range for $CO_2$ injection rate

Assume a 250 to 500 MW electrical power station using fossil fuel, the $CO_2$ 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 $d_\infty$ (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 $CH_4$ Langmuir volume, $v_L$(std-m$^3$/t) and $CH_4$ Langmuir pressure, $P_L$ (MPa), and when $CO_2$ is injected into the coal seam from a injector the cylindrical area around the injector is filled and saturated with $CO_2$. The cylindrical zone is expanding with total $CO_2$ injection amount which is equal to volume of cumulative $CO_2$ from the start of injection.

The water and $CO_2$ saturated zones are assume to be separated with the boundary $d_c$ (m) in diameter ideally without any mixing $CO_2$ 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 $CO_2$. Assume $Q$ (kg/s) is $CO_2$ mass injection rate from the injector that is function of time $t$ (s), diameter $d_c$ of the $CO_2$ saturated zone is ideally given against the cumulative injection $CO_2$ as,

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

where $\rho_C$ (kg/m$^3$) is $CO_2$ density, $dw_0$ (m) is the diameter of injection casing filled with $CO_2$ at $t$ = 0, and $\phi_C$ is total of physical porosity, $\phi_\infty$, and equivalent porosity, $\phi_e$ of coal as

$$\varphi_C = \varphi_\infty + \varphi_e \qquad (2)$$

In the model, $\phi_e$ is evaluated from the adsorption capacity $m_a$ (kg/m$^3$) and $CO_2$ density $\rho_C$ (kg/m$^3$) against coal seam temperature and pressure.

$$\varphi_e = \frac{m_a}{\rho_C} \qquad (3)$$

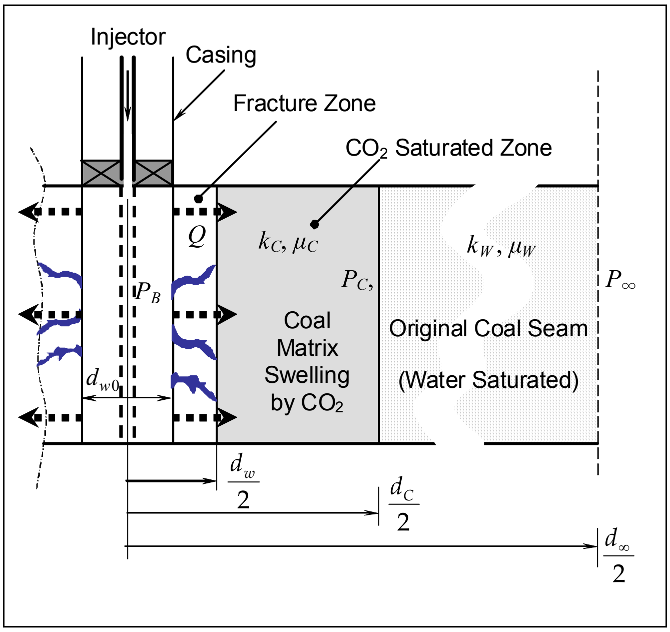

Figure 4. Schematic figure showing the radial flow model for $CO_2$ injection into coal seams (Cross section view)

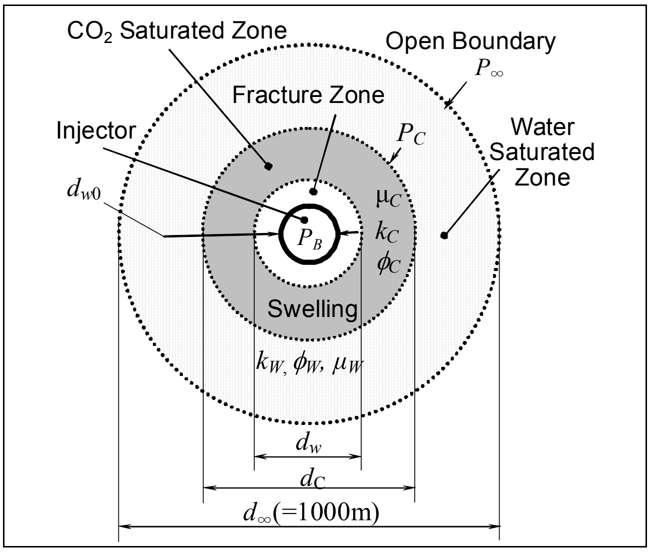

Figure 5. Radial flow model of $CO_2$ injection into coal seam (Plan view)

### 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 $k_W$ (m$^2$ or md) and $k_C$ (m$^2$ or md), respectively. In practice, the injection fluid may be changed gradually from water to supercritical $CO_2$ during a radian band. However, it is assumed that in the zone of $r \le d_C/2$, permeability $k_C$ immediately reduces from the original permeability $k_W$ by coal matrix swelling as,

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

where $\beta$ (-) 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 $P_\infty$(Pa) is the pressure at the open boundary of the independent area of coal seam, the pressure reduction against radial flows in both of $CO_2$ and water saturated zones can be given by following Darcy's law in cylindrical coordinate (Yasunami et al., 2010)

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

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

where $d_w$ is evaluated diameter tat shows the high permeability zone around the injector, $\mu_C$ (Pas) is $CO_2$ viscosity, $\mu_w$ (Pas) is water viscosity. For example, the viscosity ratio is evaluated as $\mu_C/\mu_w \approx 0.1$ for supercritical $CO_2$ condition.

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

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

Transmissibility is usually defined including the fluid viscosity and density, however the transmissibility for the initial coal seam is given as $T = hk_W$ ($m^3$) in this study, because the system includes two kinds of fluids in the seam.

Furthermore, initial $CO_2$ injection rate, $Q_0 = Q(0)$, and steady state $CO_2$ injection rate, $Q_\infty = Q(\infty)$, are expressed by following equations;

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

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

Therefore, the value of called swelling ratio $\beta$ can be evaluated from the ratio, $Q_\infty/Q_0$, times the viscosity ratio, $\mu_C/\mu_W$, as;

$$\beta = \frac{Q_\infty}{Q_0} \cdot \frac{\mu_C}{\mu_W} \tag{10}$$

## 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).

a) Set coal seam conditions; $h$, $T_\infty$, $P_\infty$, $d_\infty$, $k_W$, $\mu_W$, $\mu_C$, $\beta$ and $P_B$ at $t = t' = 0$.
b) Calculate $CO_2$ density $\rho_C$ for $T_\infty$ and $P_B$ using with the software; PROPASS.
c) Calculate the initial $CO_2$ injection rate, $Q_0 = Q(0)$ at $t = 0$ by Eq. (8).
d) Set time forward by $t = t' + \Delta t$.
e) Calculate cumulative $CO_2$ injection amount $\Sigma Q\Delta t$ from $t = 0$, and evaluate diameter $dc$ (m) by Eq. (1).
f) Calculate $Q(t)$ from Eq.(7) and set $t' = t$
g) Return to (d) and Circulate process from (d) and (f) until getting flow rate $Q(t)$ close to the steady state flow $Q_\infty$.

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

1) Height of coal seam; $h$ = 5 m
2) Coal matrix porosity; $\phi_\infty$= 0.01 (see Yamaguchi et al., 2007)
3) $CO_2$ adsorption; $m_a$ = 66 kg/$m^3$ (see Nako and Fujioka, 2007)
4) $CO_2$ density; $\rho_C$ = 860 kg/$m^3$
5) Initial temperature of coal seams; $T_\infty$ =30 °C (see Yasunami et al., 2010)
6) Pressure at open boundary; $P_\infty$=10.2 MPa
7) $CO_2$ injection pressure (BHP); $P_B$ =15.0 MPa
8) Diameter of fractured zone around $CO_2$ injector, $d_w$ = 1 to 2 m

On the other hand, values of parameters; $d_\infty$, $k_W$ and $\beta$ were evaluated with calculations matching with monitored results at Yubari ECBM pilot-test.

## 3 CALCULATİON RESULTS FOR EVALUATİON OF MODEL PARAMETERS

### 3.1 Matching procedure with monitering data

Figure 6 shows a sensitivity of initial horizontal permeability $k_W$ on $CO_2$ 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 $Q_\infty$. Figure 7 also show the sensitivity of diameter $d_\infty$ of the independent coal seam on the same $CO_2$ injection rate time curve. The results are not so much sensible to $d_\infty$. Thus, $d_\infty$ = 1000 m was used for other calculations.

Figure 8 shows sensitivity of swelling ratio $\beta$ of coal seam on $CO_2$ 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.

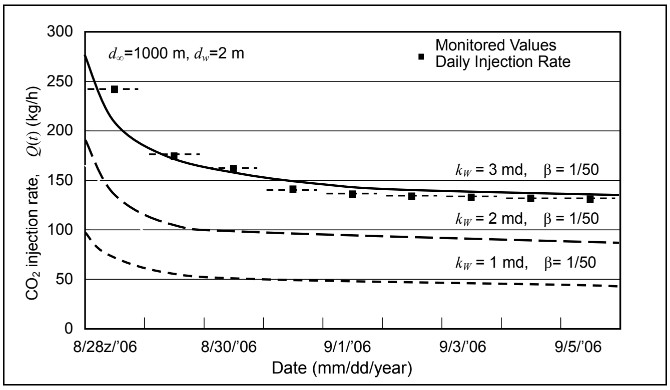

Figure 6. Sensitivity of original permeability, $k_W$ on CO$_2$ injection rate monitored at Yubari pilot test from August 28 to September 6, 2006.

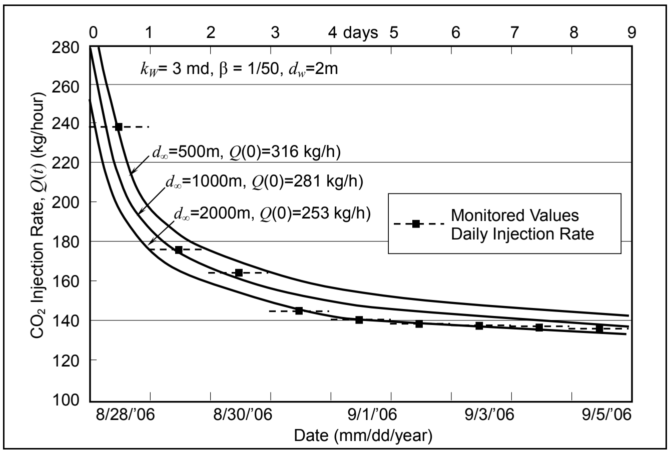

Figure 7. Sensitivity of diameter d∞ of the independent coal seam on CO$_2$ injection rate for Yubari pilot test from August 28 to September 6, 2006

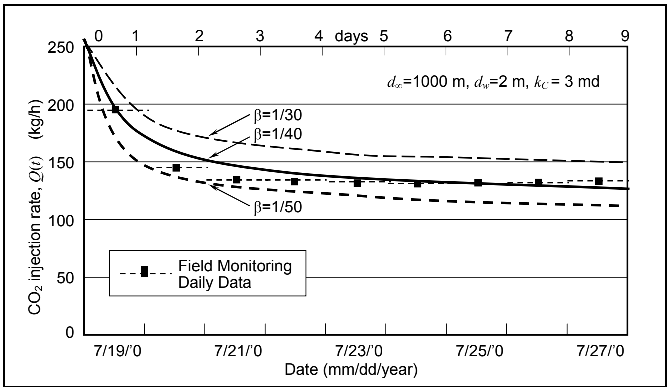

Figure 8. Sensitivity of swelling ratio $\beta$ of coal seam on CO$_2$ injection rate monitored at Yubari pilot test from July 19 to 28, 2007

### 3.2 Evaluated original permeability and swelling ratio

Figure 9 shows changing swelling ratio $\beta$ 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,

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

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 $k_C \approx 3$ md as same as the original permeability $k_W \approx 3$ 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.

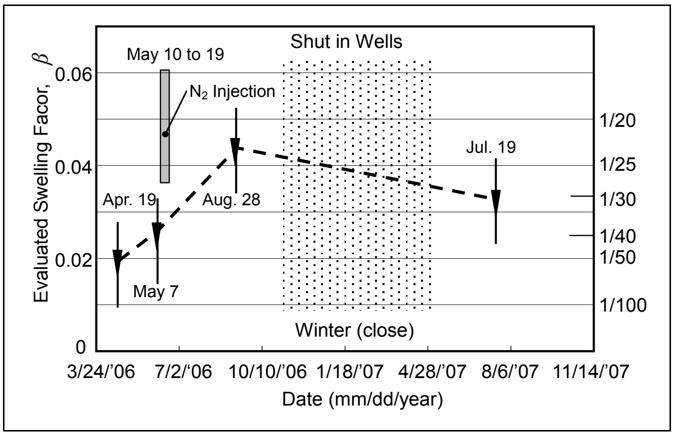

Figure 9. Evaluated swelling ratio $\beta$ for each injection test at Yubari pilot test from April, 2006 to July, 2007

## 4 CONCLUSİON

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 $CO_2$. A similar decreasing pattern in the time curves of $CO_2$ 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 $CO_2$ swelling ratio ($\beta$) that is the ratio of permeability reduction of the coal seam by coal matrix swelling in $CO_2$.saturated zone based on the assumptions that the coal seam zone is open at its outer boundary, $CO_2$ and water saturated zones are separated without mixing each other and the diameter of $CO_2$ saturated zone is expanding to cumulative injection $CO_2$.

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.

## ACKNOWLEDGEMENTS

This study was carried out as a part of a project entitled “Technology Development for Carbon Dioxide Sequestration in Coal Seams”, NEDO project on “Innovative Zero-emission Coal Gasification Power” and G-COE “Novel Carbon Science”, Kyushu University.

## REFERENCES

Law, D.H.S., Meer, L.G.H. and Gunter, W.D. (2002). Numerical Simulator Comparison Study for Enhanced Coalbed Methane Recovery Process, Part I: Pure Carbon Dioxide Injection, *Proceedings of the SPE Gas Technology Symposium (Calgary, Canada)*, SPE 75669..

The General Environmental Technos Co., Ltd. (2008). Japan CO2 Geosequestration in Coal Seams Project summary documentation (in Japanese).

Sasaki, K. and Fujii, T. (2004). Characteristics of CO2 gas permeability and adsorption of coal samples for CO2 sequestration into Japanese coal seams, *Proceedings of 7th Int. Conf. On Green House Gas Control Technology (GHGT7) (Vancouver, Canada)*, pp.2257-2261.

Fujii, T., Sugai, Y. and Sasaki, K. (2007). Characteristics of Adsorption, Permeability and Swelling of Coal Relating to Liquid CO2 Sequestration into Coal Seams (in Japanese), *Journal of MMIJ*, 123-11, 518-523 (in Japanese).

Palmer I. and Mansoori, J. (1998). P*roceedings of SPE Reservoir Evaluation & Engineering*, SPE52607.

Yasunami, T., Sasaki, K. and Sugai, Y. (2010). CO2 Temperature Prediction System in Injection Tubing Considering Supercritical Condition at Yubari ECBM Pilot-Test. *JCPT*.49-4, pp.44-50.

Maskat, M. (1937). *The Flow of Homogeneous Fluids through Porous Media*, McGraw-Hill, New York.

Yamaguchi, S., Ohga, K., Fujioka, M., and Nako, M. (2007). History Matching on Micro-Pilot Tests of CO2 Sequestration and ECBM in the Ishikari Coal Field, *Journal of Japan Institute of Energy*, 86-2, pp.80-86 (in Japanese)

PROPATH Group. (2008). Manual of PROPATH Ver 13.2.