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Numerical Simulation of CO_2 Enhanced Coal Bed Methane Recovery for a Vietnamese Coal Seam

Phung Quoc Huy[*1#], Kyuro Sasaki[*2], Yuichi Sugai[*2],
Maneeintr Kreangkrai[*2] and Tayfun Babadagli[*3]

[*1]Graduate School of Engineering, Kyushu University
[*2]Faculty of Engineering, Kyushu University
[*3]School of Mining and Petroleum Engineering, University of Alberta, Canada
[#]Present address: Institute Mining Science and Technology, Vietnam

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A CO_2-ECBMR numerical modeling has been build for the Mao Khe coal seam in Vietnam. The numerical simulations for sensitivity studies on the dominant factors for CH_4 production, such as permeability, CO_2 injection rate and well spacing have been carried out by giving CO_2 and CH_4 adsorption capacities and viscocities of CO_2 and water as a function of the coal seam temperature (40 to 65 °C). Finally, the numerical simulations with five-spot model have been presented to evaluate CO_2 injectivity and CH_4 productivity by changing the well spacing. The results show that CO_2 injection is roughly proportional to number of injectors, however the time of the maximum CH_4 production rate is delayed with 5-spots unit area. From view of economical evaluation, drilling cost of wells and well spacing are important parameters to decide the optimum production scheme.

1. Introduction

Greenhouse gases (GHGs), such as carbon dioxide (CO_2) and methane (CH_4), are increasing due to human (anthropogenic) activities. Among these GHGs, CO_2 is the most emitted greenhouse gas. CO_2 is emitted principally from the burning of fossil fuels, both in large combustion units such as those used for electric power generation and in smaller, distributed sources such as automobile engines and furnaces used in residential and commercial buildings. CO_2 emissions also resulted from some industrial and resource extraction processes, as well as from the burning of forests during land clearance.

Currently, CO_2 accounts for about 72% of the anthropogenic greenhouse effect and is the most important GHG contributor (IPCC, 2005)[1)]. Because of the large contribution of CO_2 to climate change, large reduction in CO_2 emissions will be necessary to stabilize the atmospheric CO_2 concentration.

The Kyoto Protocol (1997) calls for industrialized nations to reduce their CO_2 emissions to 95% of 1990 levels by 2012. In this regard, many national and international programs have been initiated towards understanding the magnitude and mitigation options of the greenhouse gases. The CO_2 concentration in the atmosphere could be controlled either by reducing its production releasing into the atmosphere, or by capturing and disposing of the produced CO_2 in a safe manner (storage or sequestration).

Various CO_2 storage options have been proposed, including placement in the deep oceans; placement in geologic formations (deep saline aquifers, abandoned oil or gas reservoirs, and unmineable coal seams) and consumption via advanced chemical and biological processes. These options are under investigation and on the pilot projects to determine their feasibility in terms of their storage capacity, safety, and costs. CO_2 storage in deep unmineable coal seams is one of the geologic strategies. Coal seam storage of CO_2 is particularly attractive in those cases where the CO_2 could be stored in the coal seam in an adsorbed state that is expected to be stable for geologically significant periods. Injection of CO_2 may also enhance the production of the coalbed methane recovery (CBMR) to generate a profit to help offset the expense of the CO_2 enhanced coalbed methane recovery (CO_2-ECBMR). If so, long-term storage of CO_2 in coal seams might be more cost-effective method to reduce CO_2 emission. Additionally, many power plants are located near coal seams, which would reduce the transportation costs.

In this study, a CO_2-ECBMR numerical modeling has been done for the Mao Khe coal seam in Vietnam. The numerical simulations for sensitivity studies on the dominant factors for coalbed methane gas production, such as permeability, CO_2 injection rate and well spacing have been carried out by giving CO_2 and CH_4 gas adsorption capacities and viscocities of gases and water as a function of the coal seam temperature (40 to 65 °C).

2. Numerical Simulation Modeling

2.1 CO_2-ECBMR

CO_2 adsorbs more strongly to coal than CH_4 so as CO_2 is injected into a coal reservoir, it is preferentially adsorbed into the coal matrix, displacing CH_4. The displaced CH_4 then diffuses into the cleat system and migrates to the production wells by Darcy's flow. This process is relatively efficient in theory and, as implied from the isotherms, should require 2 - 3 volumes of injected CO_2 per volume of incrementally produced CH_4 (see Huy et al., 2009)[2)].

In general, commercial projects and researches on coal bed methane (CBM) simulators were developed to model primary recovery processes, taking into account important features to properly evaluate the performance of coalbed reservoirs. To correctly model complex reservoir mechanisms in ECBMR processes using CO_2, CBM simulators are being improved to include additional features. Important features in modeling primary and enhanced coalbed methane recovery processes are as follows: a) dual porosity, dual permeability; b) multiple gas components; c) multiphase flow (gas and water) in the natural fracture system (Darcy's flow); d) pure and mixed gas diffusions between the coal matrix and the natural fracture system (different diffusion rates); e) pure and mixed gas adsorption/desorption at the coal surface (extended Langmuir isotherm relationship); f) coal matrix shrinkage/swelling due to gas desorption/ adsorption[2,6]; g) compaction/dilation of the natural fracture system due to stresses-dependent permeability and porosity models[6-9]; h) non-isothermal adsorption of the injected gas[10].

The capability to handle multiple gas components is an essential feature in modeling ECBMR processes with flue gases (Thomas et al., 2008)[3]. Recent advances in numerical simulations of CBM/ECBMR processes have focused on multi-component gas transport in the in-situ bulk coal and changes in coal properties during methane production. Considering the features required for modeling ECBMR processes, the ECLIPSE compositional simulator with a CBM module, developed by Schlumberger, was selected to conduct the simulation studies. ECLIPSE™ is a three-dimensional, finite-difference, multiphase, dual-porosity, compositional simulator. The model for simulating rock compaction is also available in ECLIPSE (Palmer and Mansoori, 1998)[4]. The simulator is capable of modeling coalbed methane reservoir performances under primary and/or enhanced recovery schemes.

Pressure reduction frees methane molecules from the coal and allows gas migration. To produce gas from coal, the adsorbed gas must first be desorbed from the coal and this is accomplished by depressurizing the coal to the critical desorption pressure. This depressurization is accomplished through the production of formation water, which exists in the natural fracture system. As the water is withdrawn and formation pressure declines, the gas volumes produced tend to build from a low initial rate to a maximum rate after several years. This is indirect contrast to conventional reservoirs, where the highest production rates are at the beginning of production and decline over the years (see Figure 1). Thus, when the

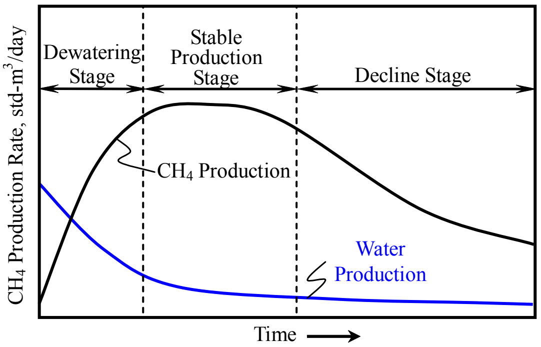

Fig. 1 Production regime in a coal seam reservoir.

initial reservoir pressure is above the critical desorption pressure, the reservoir is called an under-saturated reservoir. As the gas saturation increases in the fracture, gas flows from the matrix to the fracture and k_{rg} increases until the critical saturation is reached, when the reservoir starts producing gas with water.

2.2 Coal reservoir model and grids system

A reservoir simulation model that is one-fourth of a five-spots pattern (see Figure 2) was built using the ECLIPSE compositional reservoir simulator developed by Schlumberger. A grid sensitivity study used a single-layer grid model from 22×22×30 to 72×72×30 grid cells in a 5-spots pattern with the dimensions of the coal reservoir from 110×110×8.4 m to 360 × 360×8.4 m (see Table 1).

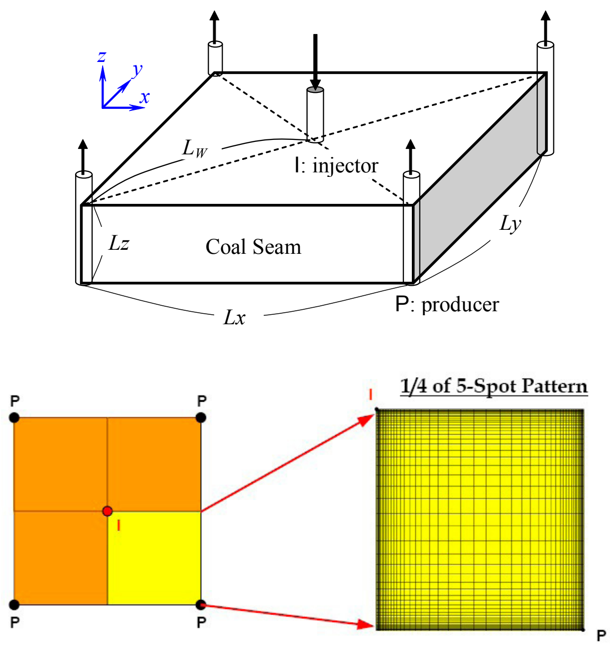

Fig. 2 Diagram of the five spots model.

Table 1 Numerical parameters for five-spot model

Well distance L_W (m)	Dimension of well span (L_X×L_Y×L_z) (m)	Area of 1/4 of 5-spot (m^2)	Total number of grid blocks (=n_X×n_Y×n_Z)
78	110×110×8.4	3025	22×22×30=14520
106	150×150×8.4	5625	30×30×30=27000
156	220×220×8.4	12100	44×44×30=58080
205	290×290×8.4	21025	58×58×30=100920
255	360×360×8.4	32400	72×72×30=155520

2.3 Adsorption isotherms and diffusion

In this paper, a coal seam at Maokhe coal mine was selected for this study. As the important parameter of coal, CH_4 and CO_2 adsorption of the coal have been measured and the results are shown in Figure 3.

Langmuir constants of samples MK-9D have been selected as input parameters for modeling. The Langmuir constants for CH_4 and CO_2 are shown in Table 2.

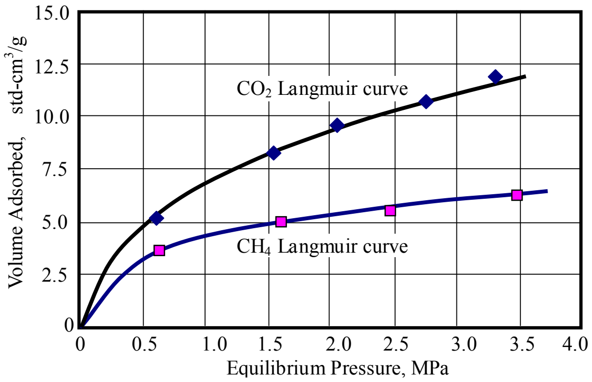

Fig. 3 CO_2 and CH_4 Langmuir curves for Mao Khe coal samples[2,5,7,8].

Table 2 Input parameters for numerical simulations

Parameters for numerical simulation	Units	Value
Coal Matrix Porosity	-	0.01
x- direction Permeability, *kx*	mD	1.0
y- direction Permeability, *ky*	mD	1.0
z- direction Permeability, *kz*	mD	0.1
Initial Pressure of Coal, P_{int}	MPa	5.5
Temperature of Coal Seam, *T*	°C	45
Coal Thickness, *m*	m	8.4
Depth of Reservoir, *D*	m	524
Initial CH_4 Saturation	-	0.05
Initial Water Saturation	-	0.95
CH_4 Desorption time, τ,	day	20
CO_2 Desorption time, τ;	day	10
CH_4 Langmuir Volume, V_L	m³/t	7.35
CH_4 Langmuir Pressure, P_L	MPa	0.76
CO_2 Langmuir Volume, V_L	m³/t	15.58
CO_2 Langmuir Pressure, P_L	MPa	1.24
CO_2 Injection Pressure (BHP)	MPa	8
Production Pressure (BHP)	MPa	0.14

* BHP= Bottom Hole Pressure, mD = 10^{-15}m^2 (SI unit)

In this model, the extended Langmuir isotherm was applied as follows:

$$G_{si} = G_{sLi}\left[1-\left(w_a + w_{we}\right)\right]\frac{\dfrac{p\delta_i}{p_{Li}}}{1+p\sum_{j=1}^{nc}\dfrac{\delta_j}{p_{Lj}}} \quad (1)$$

where G_{si} = multi-components storage capacity of component i (m³/t); G_{sLi} = single component Langmuir storage capacity of component *i* (m³/t); w_a = ash content (%); w_{we} = equilibrium moisture content (%); p_{Li} or p_{Lj} = single component Langmuir pressure of component i or j (MPa); δ_i or δ_j = mole fraction of component *i* or *j* in the free gas phase (%); n_c = number of components; p = pressure of free gas phase (MPa).

The diffusive flow between the matrix and the fracture is given by

$$F_i = D_{c,i}.S_g.RF_i(m_i - \rho_c L_i) \quad (2)$$

where m_i = molar density in the matrix coal; ρ_c = rock density (coal density) (kg/m³); $D_{c,i}$ = diffusion coefficient (coal) component *i*; RF_i = read sorption factor component *i*; S_g = gas saturation

2.4 Sensitivity analysis for CO_2-ECBMR

The success of a CO_2-ECBMR process is dependent on a number of operating parameters such as injection pressures and producer-injector spacing. Other factors dominating the process are determined by the actual static and dynamic qualities of the reservoir. To reduce risk in a new CO_2-ECBMR project, a sensitivity analysis should be carried out to obtain the optimized well spacing, CO_2 injection rate and the end point of CH_4 production. This study analyzes the sensitivity in four parameters as next sentences.

2.4.1 Sensitivity of CO_2 injection

Comparison of the base case model (no CO_2 injection gas) and the CO_2 injection model with a wells spacing of L_W = 106 m and an injection pressure of P_{inj} = 8 MPa.

2.4.2 Sensitivity of injection-production well spacing

Assuming a constant injection pressure P_{inj} = 8 MPa, different wells spacing were investigated L_W = 78, 106, 156, 205 and 255 m.

2.4.3 Sensitivity of permeability

Assuming a fixed well spacing L_W = 106 m and a constant CO_2 injection pressure P_{inj} = 8 MPa, different permeabilities were investigated *k* = 0.5, 1 and 2 mD.

2.4.4 Sensitivity of coal seam temperature

Assuming a fixed well spacing L_W = 106 m and constant CO_2 injection rate P_{inj} = 8 MPa and permeability *kx* = *ky* = 1 mD, different temperatures were investigated *T* = 40, 50 and 65 °C.

3. Simulation Results And Discussion

3.1 Saturation of gases

CO_2 and CH_4 saturation in the Mao Khe model are shown in Figures 4 and 5, for operating times of 3, 6, 9 and 12 months. The well spacing in this case was 156 m and the permeability was *kx* = *ky* = 1 mD. The results show that CH_4 and CO_2 saturation were slow because of their low permeabilities. At a time of 12 months after the wells were opened, the CO_2 and CH_4 saturation levels were about 40% of total saturation.

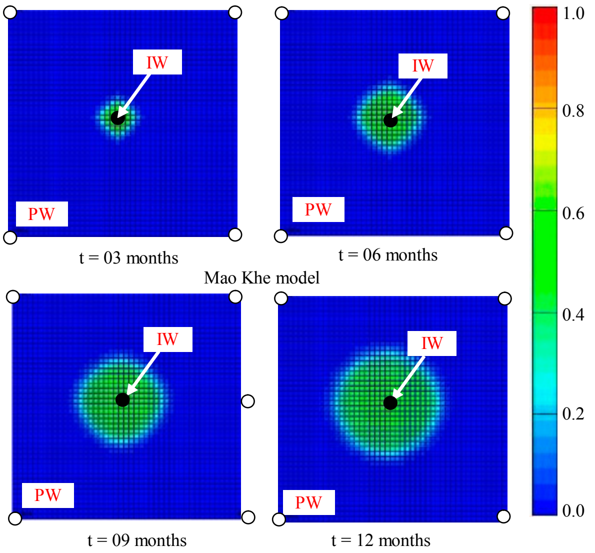

Fig. 4 CO_2 saturation at different operating times.

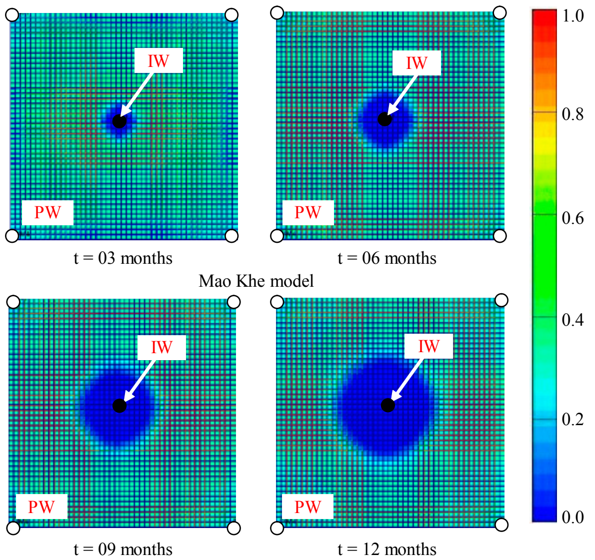

Fig. 5 CH_4 saturation at different operating times.

3.2 Gas injection sensitivity analysis

Comparison of the base case model (no gas injection) and the CO_2 injection model were carried out. The operating parameters in this sensitivity analysis are shown in Table 3.

Table 3 Operating parameters for sensitivity analysis

Operating Parameters	Units	Value
CO_2 Injection (BHP)	MPa	Shut-in / 8 MPa
Producer-Injector spacing, L_W	m	106
Production Pressure (BHP)	MPa	0.14
Reservoir Initial Pressure, P_{int}	MPa	5.5
x-direction Permeability, *kx*	mD	1.0
y-direction Permeability, *ky*	mD	1.0
z-direction Permeability, *kz*	mD	0.1
Temperature of Coal Seam, *T*	°C	45

Figure 6 shows the CH_4 production rate by CO_2 injection (CO_2-ECBMR) and without CO_2 injection (CBM). The CO_2-ECBMR results show that CO_2 injection enhanced the maximum CH_4 production rate by 195%, from 2069 to 4052 sdt-m^3/day. Cumulative CH_4 production also increased 168% from 1.2×105 to 2.0×10^5 std-m^3 with CO_2 injection. The CH_4 production rate reached the maximum at around 6 months after start of operation and then declined gradually. It was applied to numerical simulations as an operation strategy that CH_4 production well is shut down when the CO_2 concentration in the producer exceeds 20%, since it would be costly to separate CO_2 from CH_4. In the operation, water in the coal seam is produced initially, and then CH_4 is produced. Water production in CO_2-ECBMR is around one month faster than that of CBMR. The production rate increased sharply after the first month and reached a maximum production rate at around the 6th month. Without CO_2 injection, water production resulted from the natural water pressure in the coal reservoir (5.5 MPa). Thus, water remained in the coal seam, leading to a lower CH_4 production rate. Furthermore, CO_2 molecules could displace CH_4 molecules and enhance CH_4 recovery.

In summary, the CO_2-CBMR processes gives the dual benefits of enhancing CH_4 production and storage of CO_2. Enhancing the CH_4 production increases revenues from selling the gas and improves the gas recovery factor from the coal reservoir. CO_2 stored in the coal seams may also generate revenue from environmental funds.

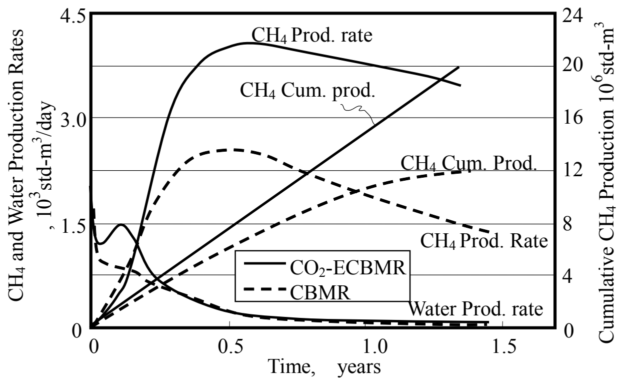

Fig. 6 Comparisons of CH_4 production by ECBMR and CBMR (with and without CO_2 injection).

3.3 Injection – production wells spacing sensitivity analysis on economic evaluation

CO_2 Capture and Storage (CCS) technology has been approved as a method for clean development mechanism (CDM) projects. Therefore, economic evaluation including CO_2 credits is important. Sensitivity study of injection-production well spacing on the injection and production rates is an effective approach to decide the optimized well-spacing and shut-in time of CH_4 producer. These simulations are used be helpful to reduce operation cost and economic risks included in CO_2-ECBMR projects.

In this study, the sensitivity analysis of injection-production well spacing for the Mao Khe coal seam model was carried out by simulating the CO_2 injection process into the coal seam model with five different injector-producer well-spacings; L_W = 78, 106, 156, 205 and 255 m. The operating parameters used in this analysis are shown in Table 4.

Table 4 Operating parameters for sensitivity analysis on injector-producer well-spacing

Operating Parameters	Units	Value
CO_2 Injection Pressure(Bottom Hole)	MPa	8
Producer-Injector spacing, L_W	m	78, 106, 156, 205, 255
Production Pressure (Bottom Hole)	MPa	0.14
Reservoir Initial Pressure, P_{int}	MPa	5.5
x-direction Permeability, *kx*	mD	1.0
y- direction Permeability, *ky*	mD	1.0
z- direction Permeability, *kz*	mD	0.1
Temperature of Coal Seam, *T*	°C	45

Figure 7 shows the CO_2 injection and CH_4 production rates using with different L_W. The results show little difference in the maximum CH_4 production rates between the cases. The CH_4 production and for CO_2 injection rates were approximately 4000 and 10,000 std-m^3/day, respectively . The CH_4 production rate of L_W = 78m was slightly higher than other L_W and the shut-in time of the producer was less than one year.

The cumulative injection/production of CH_4 and CO_2 for different well-spacings are shown in Figure 8. The results show that cumulative CH_4 production in the case of L_W = 255 m was the highest. The cumulative CH_4 production was 1.25×10^6 sdt-m^3 in 8.4 years after the wells were opened. In the case of L_W = 106 m, the cumulative CH_4 production was 2.7×10^5 sdt-m^3 in 1.4 years. The result of L_W = 78 m had the smallest cumulative CH_4 production and the shortest production period and it was excluded from present study.

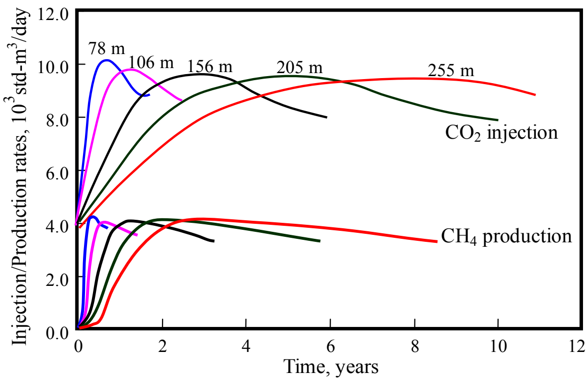

Fig. 7 CO_2 injection and CH_4 production for different well-spacings.

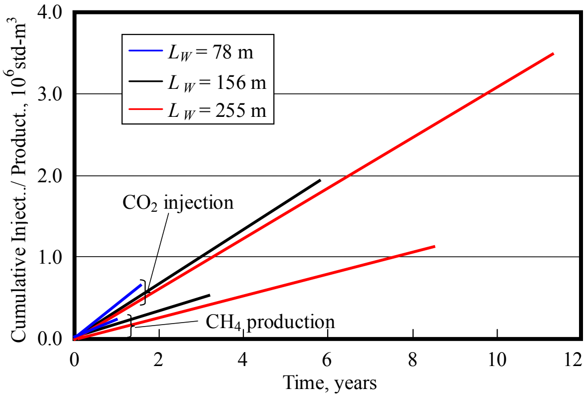

Fig. 8 Cumulative CO_2 injection and CH_4 production for different well-spacings.

To optimize the well-spacing in present CO_2-ECBMR model, the economic evaluation has been carried out. The parameters for optimizing well spacing are shown in Table 5. Total profit per unit area was calculated by the following equation:

Table 5 Parameters for optimization of well spacing

Economic Parameters	Well spacing L_W = 78 m	L_W = 106 m	L_W = 156 m	L_W = 205 m	L_W = 255 m
Drilling cost (*D*), US$	200,000	200,000	200,000	200,000	200,000
Production duration (*t*), year	0.70	1.40	3.20	5.80	8.40
Maintenance cost per year (*m*), US$	20,000	20,000	20,000	20,000	20,000
Maintenance cost (*M*), US$	14,000	28,000	64,000	116,000	168,000
Production areas (*A*), m^2	3,025	5,625	12,100	21,025	32,400
Cum. CH_4 production (P_{CH_4}), std-m^3	250,000	275,000	490,000	850,000	1,250,000
Cum. CO_2 injection (P_{CO_2}), std-m^3	650,000	800,000	1,950,000	3,200,000	4,000,000
Income from CH_4 (I_{CH_4}), US$	110,000	121,000	215,600	374,000	550,000
Income from CO_2 (I_{CO_2}), US$	32,500	40,000	97,500	160,000	200,000
Recovery factor for duration, R_f	0.90	0.90	0.77	0.75	0.63
Benefit (*B*), US$	-85,750	-83,100	-22,913	84,500	104,500
Present value/ Unit Area (*B*/*A*), US$/m^2	-28.3	-14.8	-1.9	4.0	3.2

$$\frac{B}{A} = \frac{(I_{CH_4} + I_{CO_2})R_f - (D+M)}{2L_W{}^2} \quad (3)$$

where B = total benefit (US\$); I_{CH_4} = income from CH_4 (US\$); I_{CO_2} = income from CO_2 (US\$); R_f = capital recovery factor; D = drilling cost (US\$); M = maintenance cost (US\$); A = unit area of 5-spot (m^2).

In this study, the CH_4 gas price was evaluated as US\$0.4 /m^3 and CO_2 was US\$0.05/m^3. The results of the economic analysis showed that the Mao Khe model had maximum benefit (B = US\$104,500) at well spacing of 255m. Because of the high drilling cost, the well-spacing $L_W \leq 205$m was not economically feasible. However, the benefit per unit area of coal reservoir was highest (B/A = US\$4.0/m^2) at L_W = 205m. This means that L_W = 205 m can be considered as the best selection based on present sensitivity analysis (Figure 9).

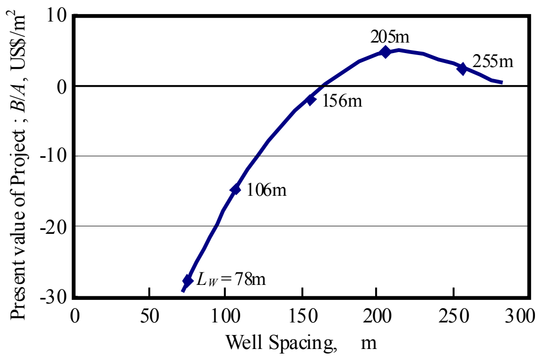

Fig. 9 Present value of B / A for various well-spacings.

Figure 10 showed the relationship between optimized well spacing and drilling cost. The result showed that optimized well spacing increase when increasing of drilling cost.

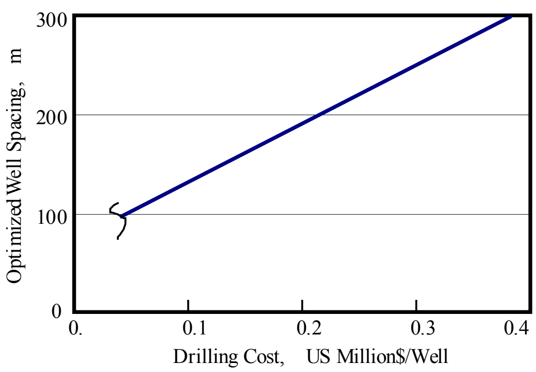

Fig. 10 Drilling cost for various well-spacings.

Using a similar analysis to this study, the sensitivity for other well-spacings can be carried out so that an optimized well spacing can be obtained for the actual conditions of CO_2-ECBMR projects.

The sensitivity analysis of well-spacing between injection and production wells was an useful approach for deciding the optimized well-spacing and the time to shut down CH_4 production and injection of CO_2. This reduces the cost of operation and risks in CO_2-ECBMR projects.

3.4 Permeability sensitivity analysis

The operating parameters used in this analysis are shown in Table 6. CO_2 injection and CH_4 production rates for $kx = ky$ = 0.5, 1 and 2 mD have been shown in Figure 11. The results show that both rates increased with reservoir $kx = ky$, but CH_4 production period decreased. In the case when permeability $kx = ky$ = 2 mD was given, the CO_2 injection rate was approximately 1.7×10^4 std-m^3/day. And it was almost twice to the case of 1mD and about 4 times larger than that of 0.5 mD (i.e. CO_2 injection rate is roughly proportional to permeability).

Table 6 Operating parameters for permeability sensitivity analysis

Operating Parameters	Units	Value
CO_2 Injection Pressure (BHP)	MPa	8
Producer-Injector spacing, L_W	m	106
Production Pressure (BHP)	MPa	0.14
Reservoir Initial Pressure, P_{int}	MPa	5.5
x-direction Permeability, kx	mD	0.5, 1.0, 2.0
y-direction Permeability, ky	mD	0.5, 1.0, 2.0
z-direction Permeability, kz	mD	0.05, 0.1, 0.2
Temperature of Coal Seam, T	°C	45

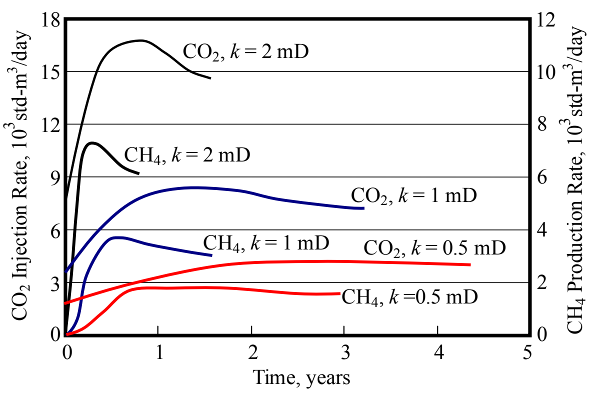

Fig. 11 Injection and production rate of gases for different permeabilities.

3.5 Temperature sensitivity analysis

Injection rate against some coal seam temperatures were investigated (Figure 12). The numerical parameters for this sensitivity analysis are shown in Table 7. The results show that a higher temperature gave a smaller injection rate. The gas adsorption capacity of coal depends on temperature (Huy, et al., 2009)[6] (Sasaki, et al., 2009)[7]. The adsorption volume was reduced with increasing temperature. Therefore, injection rate also be reduced with increasing temperature.

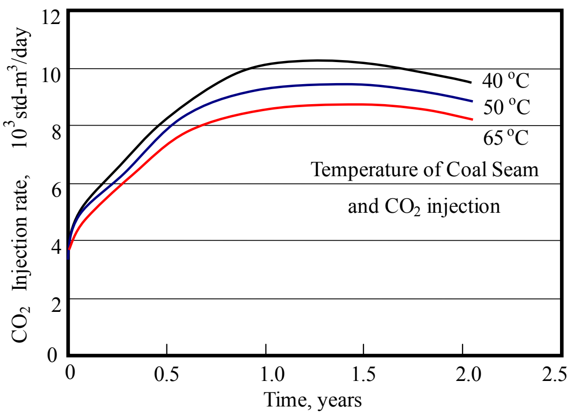

Fig. 12 CO_2 injection rate against different coal seam and CO_2 temperatures.

Table 7 Operating parameters for temperature sensitivity study.

Operating Parameters	Units	Value
CO_2 Injection Pressure (BHP)	MPa	8
Producer-Injector Spacing, L_W	m	106
Production Pressure (BHP)	MPa	0.14
Reservoir Initial Pressure, P_{int}	MPa	5.5
x-direction Permeability, kx	mD	1.0
y- direction Permeability, ky	mD	1.0
z- direction Permeability, kz	mD	0.1
Temperature of Coal Seam, T	°C	40 50 65

4. Conclusions

Coal bed methane production by CO_2 injection into coal seams (CO2-ECBMR) is expected as a cost-effective CO_2 sequestration method, since financial benefit from gas production can offset some of investment for CO_2 capture process. In this study, the sensitivity analysis with the numerical simulation results was carried out to investigate the dominant model factors of CO_2-ECBMR for the Mao Khe coal seam in Vietnam.

The following conclusions are summarized.

1. Numerical simulation results using five-spot model at the Mao Khe coal seam have shown that the CH_4 production by CO_2 injection is increased by 195% compared with usual CBM.
2. A sensitivity analysis of CO_2 injection pressure gives a useful information to decide the CH_4 production period and to carry out economic evaluations.
3. In the Mao Khe model built in this study, the well spacing of 205 m was found to be optimal because the CH_4 production rate was maximized, giving the highest present value. Additionally, CO_2 was stored at the maximum injection rate.

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References

1) IPCC, *IPCC special report on carbon dioxide capture and storage*, Cambridge University Press, N.Y. (2005).
2) P. Q. Huy, K. Sasaki, Y. Sugai, T. Kiga, M. Fujioka, T. Adachi, *JCPT (SPE)*, **48**(10), 58-63 (2009).
3) G. Thomas and B. Dale, International Journal of Coal Geology, **74**, 215-236 (2008).
4) I. Palmer, J. Mansoori, *SPE Reservoir Evaluation & Engineering*, December, SPE52607 (1998).
5) P. Q. Huy, K. Sasaki, Y. Sugai, *Proc. of 4th Int. Workshop on Earth Science and Technology*, 271-278 (2006).
6) P. Q. Huy, K. Sasaki, Y. Sugai, S. Ichikawa, T. Babadagli, *Proc. of International Symposium on Earth Science and Technology 2009*, 145-150 (2009).
7) K. Sasaki, T. Yasunami, Y. Sugai, *Journal of MMIJ*, **125**(12), 605-613 (2009).
8) K. Sasaki, K. Fujii, S. Yamaguchi, K. Ohga, K. Hattori, Y. Kishi, *Journal of MMIJ*, **120**(8), 461-458 (2004).
9) P. Q. Huy, K. Sasaki, Y. Sugai, S., *Int. Journal of Coal Geology*, **81**(4), in printing (2010).
10) T. Yasunami, K. Sasaki, Y. Sugai, *JCPT(SPE)*, **49**(4), 44-50 (2009).