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NUMERICAL MODELLING AND SIMULATION OF CO_2 –ENHANCED COAL-BED METHANE RECOVERY (CO_2-ECBMR): THE EFFECT OF COAL SWELLING ON GAS PRODUCTION PERFORMANCE

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Abstract

This presents study investigate the effect of swelling on gas production performances at coal reservoirs during CO_2-ECBMR processes. The stress-dependent permeability-models to express effect of coal matrix shrinkage/swelling using Palmer and Mansoori (P&M) and Shi and Durucan (S&D) models were constructed based on present experimental results for typical coal reservoirs with the distance of 400 to 800 m between injection and production wells. By applying the P&M and S&D models, the numerical simulation results showed that CH_4 production rate was decreasing and peak production time was delayed due to effect of stress and permeability changes caused by coal matrix swelling. The total CH_4 production ratio of swelling effect/no-swelling was simulated as 0.18 to 0.95 for permeability 1 to 100 mD, respectively. It has been cleared that swelling affects gas production at permeability 1 to 15 mD, however, it can be negligible at permeability over 15 mD.

Keywords: *Coal swelling in CO_2, Permeability, Low rank coal, CO_2-ECBMR*

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1 Introduction

In regard to simulate the effect of swelling and others factors in field scale, a numerical modelling of CO_2-ECBMR has been constructed. The reservoir simulator used for the study was ECLIPSE E300, 2012.1 by Schlumberger (Schlumberger, 2012) which have incorporated dual porosity model, sorption and diffusion processes, as well as coal shrinkage and compaction effects. A modified Warren and Root model (Warren and Root, 1963) have been used to describe dual porosity process in coal bed methane model. The adsorbed concentration on micro-pore in coal surface is assumed to be a function of pressure only and described by Langmuir isotherm. To accommodate different gases on CO_2-ECBMR project, an extended Langmuir isotherm is used to describe the coal sorption for different components. The diffusive flow of gas from the matrix to cleat system is given by Fick's law while from cleat to well be governed by Darcy law. Rock compaction is used to model the compression and expansion of the pore volume and its effect on permeability.

The main objectives of this study was to examine the swelling effect on coal permeability based on stress-dependent permeability model related to gas production.

2 Reservoir Model Construction

Some parameters determined from experimental results as well as synthetic data were used as input parameters for numerical simulations as described in Table 1. A sensitivity study have been conducted to investigate the effects of some parameters on gas production. The values of parameters in base case were set and either lower or higher values were determined for sensitivity studies.

To reduce total grid cell and to optimize the computational speed, well spacing were modelled as ¼ model as shown in Figure 1. Synthetic data and isotropic block model were used instead of real field data. Thus full model data was based on a multiply of ¼ model.

3 Numerical Model Result

One of the main objectives to carry CO_2 injection into coal reservoir is to enhance CH_4 production (CO_2-ECBMR) compared to primary CH_4 recovery. Figure 2 shows the comparison of CH_4 production rate for the primary recovery and CO_2-ECBMR processes as function of time. The results indicate the enhancement of CH_4 gas production due CO_2 injection.

Since the purpose of CO_2-ECBMR is also to store CO_2 in coal reservoirs, thus after CO_2 breakthrough occurs in a production well, the injected CO_2 will stop. In this study, a threshold of 10% CO_2 in production well was applied to shut off the injection well. Detail of numerical simulation results could be checked on Table 2. With this scenario, the maximum CH4 production rate was 48.80×106 m^3 for primary recovery, while 5 spot base model resulted 74.40×106 m^3. This means it was increasing up to 65.59 %. Moreover, gas recovery with 5-spot base model was 83% for 17 years well operation compared to 54 % by CBM processes for 25 years. Moreover, in case of CO_2-ECBMR base model, 146.40×106 m^3 of CO_2 was injected to the coal reservoir. This was the advantage of CO_2-ECBMR which not only to enhance CH_4 production but also to store CO_2 in the reservoirs. In this study, total CO_2 injection was around 1.5 to 2 times higher than total CH_4 production. It is due to the fact that CO_2 is adsorb higher than CH_4 at given pressure. Additionally, higher total CH_4 production rate was achieved in faster time by CO_2-ECBMR processes.

In Figure 2, peak production for CO_2-ECBMR was higher than the CBM processes. However, it was reached slightly slower than the CBM processes. In CO_2-ECBMR, CO_2 displace CH_4 and cleat pressure is kept high, thus faster flow is resulted. Hence, slower achieving peak production is mainly due to the higher CH_4 production rate in CO_2-ECBMR model compared to the case by primary recovery.

As shown in Anggara *et al.* (2014), matrix shrinkage and swelling due to CH_4 desorption and CO_2 adsorption are observed when CO_2 is injected into coal reservoir. The estimation of the effects of swelling and effective stress on permeability is more important rather than estimated absolute permeability which is highly sensitive to the scale of measurement and has been shown to be a property which can only reliably be determined from well testing and history matching (Pan *et al.*, 2010). In this study, those effects on coal permeability is expressed by both of Palmer and Mansoori (P&M) and Shi and Durucan (S&D) models as referred to Palmer and Mansoori (1998); Shi and Durucan (2005).

The permeability ratio calculated using P&M as well as S&D model as function of pressure is plotted in Figure 3. Stress-dependent permeability was used in numerical modelling to simulate the effect of swelling as well as effective stress on production performance.

Figure 4 shows the comparison of production performances as a function of time in respect to Young's modulus effect based on the P&M model. It was observed that CH_4 production rate was lower and peak production was delayed due to stress and matrix shrinkage/swelling in numerical simulations.

Furthermore, lower initial CH_4 production rate was observed in case of lower Young's modulus and it mainly due to larger compaction effect in the region near producer well when the pressure decrease. Compared to the result by the S&D model in Figure 5, CH_4 production rate was lower than the P&M model

Table 1: Input parameters for present numerical simulations.

Coal properties			
Coal seam thickness (m)	10		
Top of coal seam (m)	1000		
Density (kg/m^3)	1320		
Porosity	0.008		
CH_4 Langmuir pressure (P_L, MPa)	3.16		
CO_2 Langmuir pressure (P_L, MPa)	2.10		
CH_4 Langmuir volume (V_L, m^3/kg)	0.0151		
CO_2 Langmuir volume (V_L, m^3/kg)	0.0361		
CO_2 Langmuir strain (□$_L$, %)	2.53		
CO_2 Langmuir pressure (P_L, MPa)	4.17		
CH_4 Langmuir strain (□$_L$, %)	1.28		
Poisson's ratio (□)	0.39		
Initial reservoir condition			
Temperature (°C)	55		
Pressure (MPa)	7.5		
Initial water saturation (%)	100		
Operating condition (full well, 5-spot model)			
CO_2 injection rate (ton/d)	40		
Maximum bottom-hole pressure (MPa)	10		
Maximum gas production rate (m^3/d)	100,000		
Minimum bottom-hole pressure (MPa)	0.275		
Sensitivity study		Base case	
Young modulus (MPa)	1.60x10^3	No effect	3.068x10^3

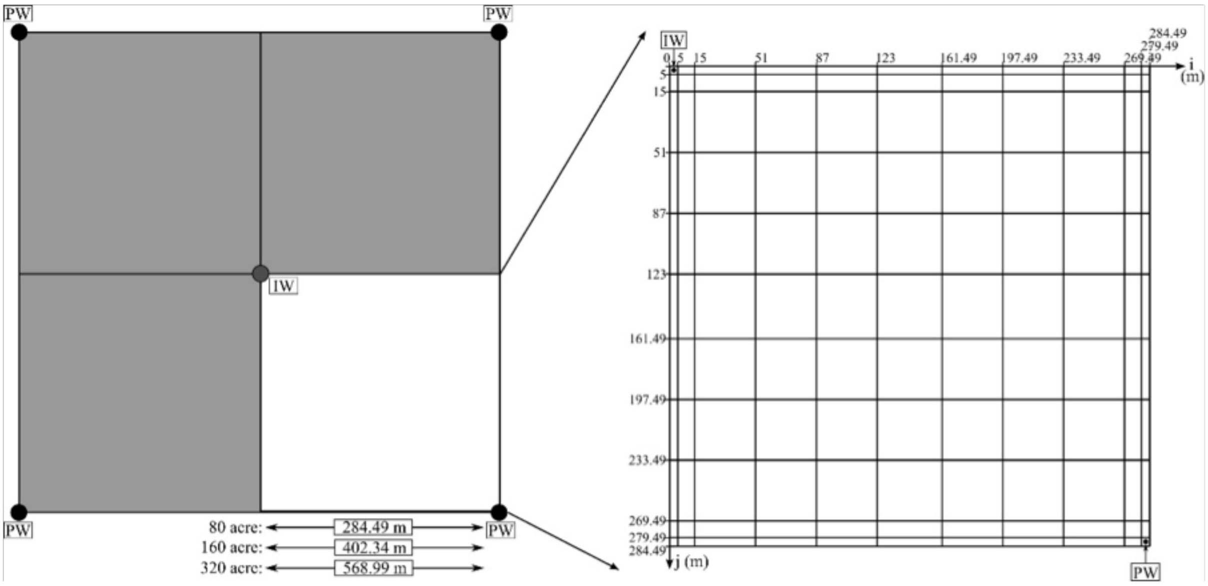

Figure 1: ¼ 5-spot model, well spacing diagram (PW: production well, IW: injection well).

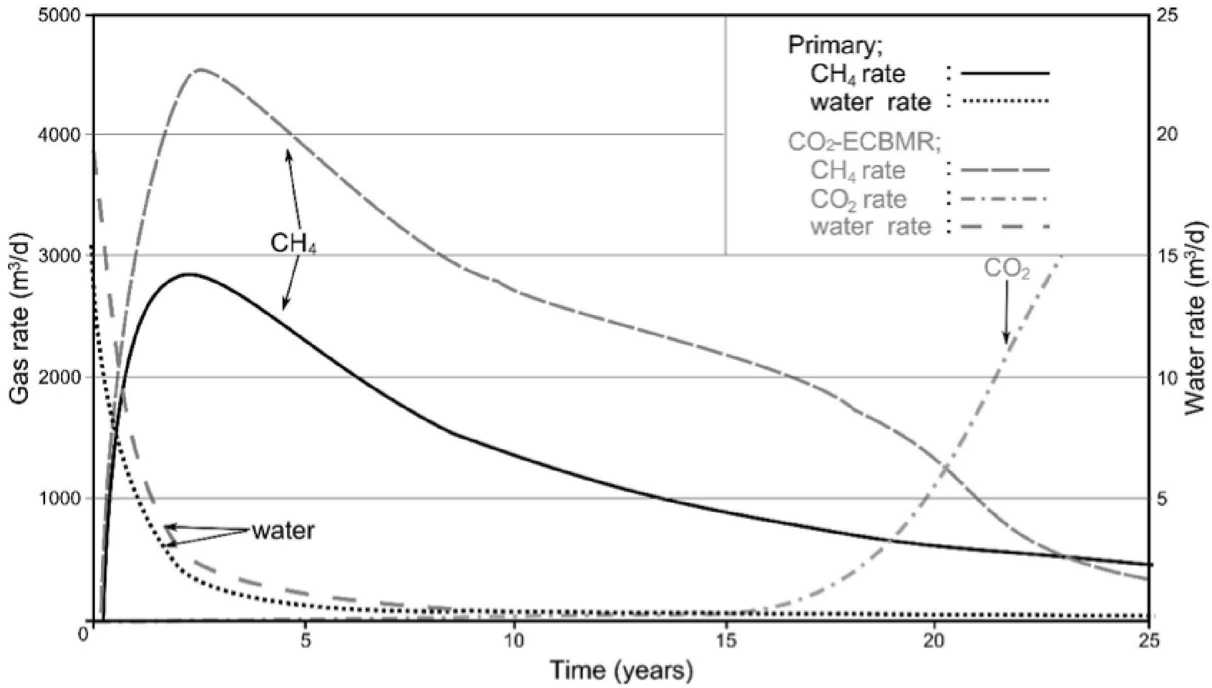

Figure 2: The comparison of gas production by CBM and CO_2-ECBMR processes.

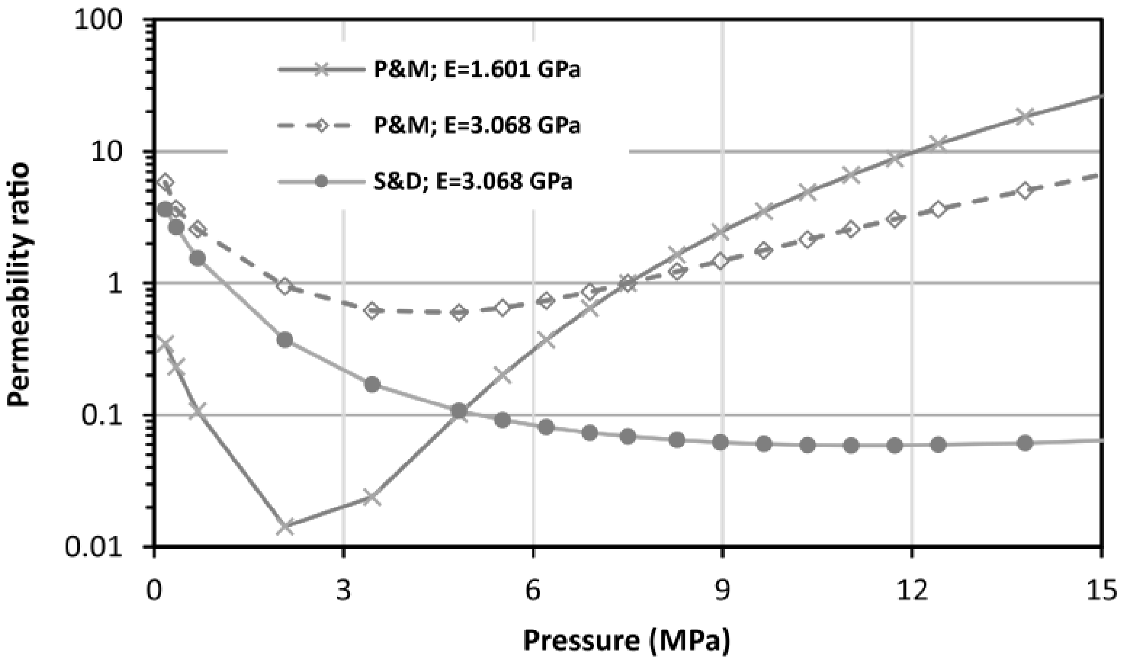

Figure 3: Stress-dependent permeability used in the numerical simulation.

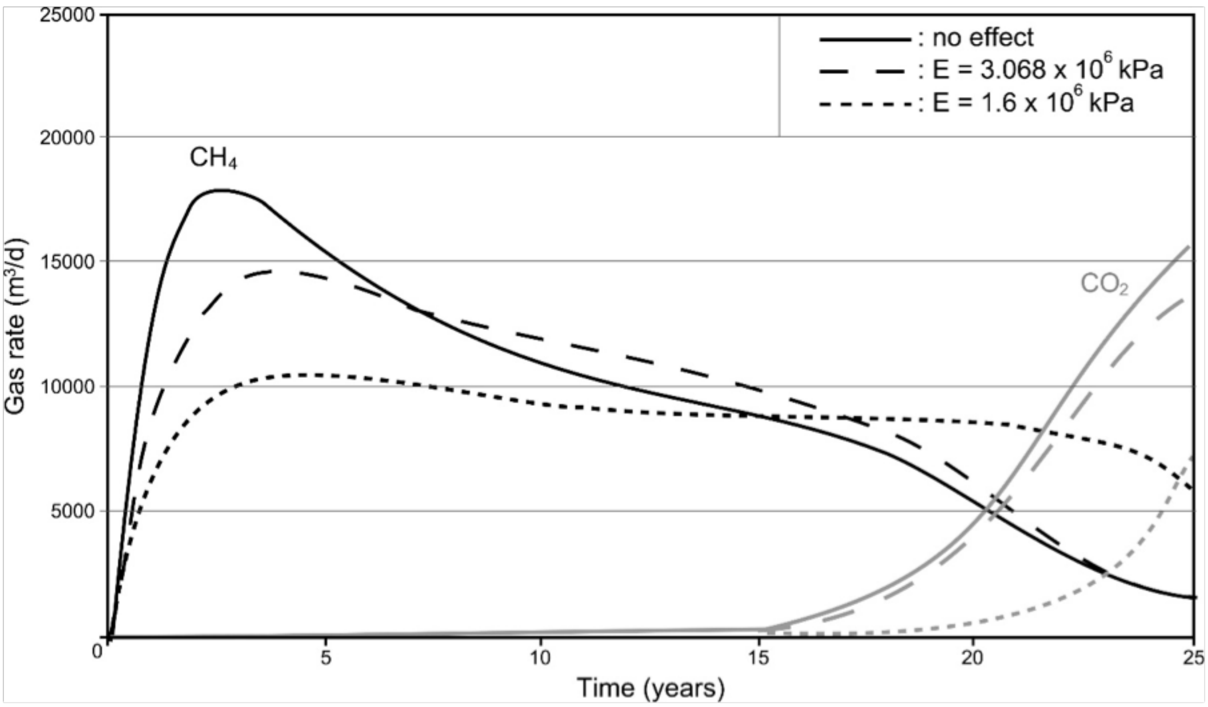

Figure 4: The comparison of the effect of volumetric strain on well performance as function of time using the P&M model.

Table 2: Summary of numerical simulation results.

Parameters		Total CH_4 production ($\times 10^6$ m^3)	Total CO_2 injection ($\times 10^6$ m^3)	RF (%)	Peak production Rate ($\times 10^3$ m^3)	Peak production Time (years)	Life time (years)
Primary		48.80	-	54.45	11.46	2.36	25.00
Base model		74.40	146.40	83.02	18.00	2.63	16.87
Young's modulus ($\times 10^6$ kPa); P&M	1.60	70.80	187.60	79.00	10.37	3.73	21.53
	3.01	73.60	149.20	82.12	14.63	3.86	17.15
Young's modulus ($\times 10^6$ kPa); S&D	3.01	72.40	161.20	80.78	13.03	5.10	19.75
GIP ($\times 10^6$ m^3)		80 acre	Base model		320 acre		
		45.03	89.62		180.13		

with same Young's modulus value. It was caused by the S&D model that has matrix shrinkage/swelling effect 1.6 to 2.1 stronger than the P&M model that depends on the Poisson's ratio.

4 Discussion

Published permeability data for coals in Indonesia are limited. Sosrowidjojo (2006) reported coal permeability from South Palembang basin varies between 2–10 mD. In comparison, Zarrouk and Moore (2009) reported coal permeability of Huntly coal seams, New Zealand between 1–15 mD for identical coal rank.

A comparison between total CH_4 productions as function of coal permeability was shown in Figure 6. As discussed previously that initial higher permeability tend to achieve rapid increase of gas production, it also confirmed that increasing total CH_4 productions was achieved with increasing permeability.

The ratio of total CH_4 productions with swelling/no-swelling effect by P&M and S&D model was presented in Figure 7 to examine the effect of coal swelling. The coal swelling affect total CH_4 production at permeability between 1–10 mD. However, in the case of permeability higher than 15 mD, the swelling effect was negligible.

Total CO_2 injection as function of permeability are shown in Figure 8. There is a tendency of decreasing total CO_2 injection with increasing permeability. It is due to the fact that in permeability higher than 15 mD, CO_2 will breakthrough faster in production well and contaminate the CH_4 production. As mentioned previously that injection well will be shut-in when 10% of CO_2 was detected in production well. Thus, decreasing total CO_2 injection with increasing permeability was in correlation with well-life time. As shown in Figure 9, well-life time decrease with increasing permeability. However, in the low permeability (less than 5 mD), total CO_2 injection was quite low and it is due to low CO_2 injectivity.

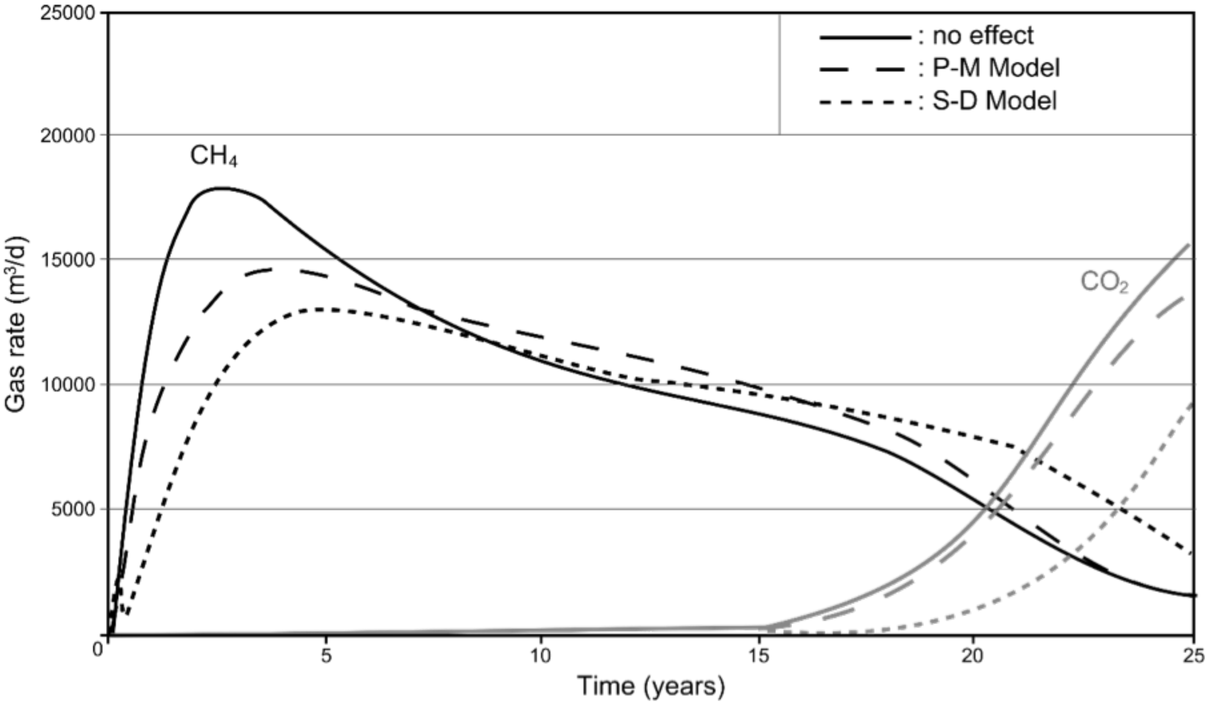

Figure 5: Comparison of the effect of volumetric strain on well performance as function of time based on the P&M and S&D model.

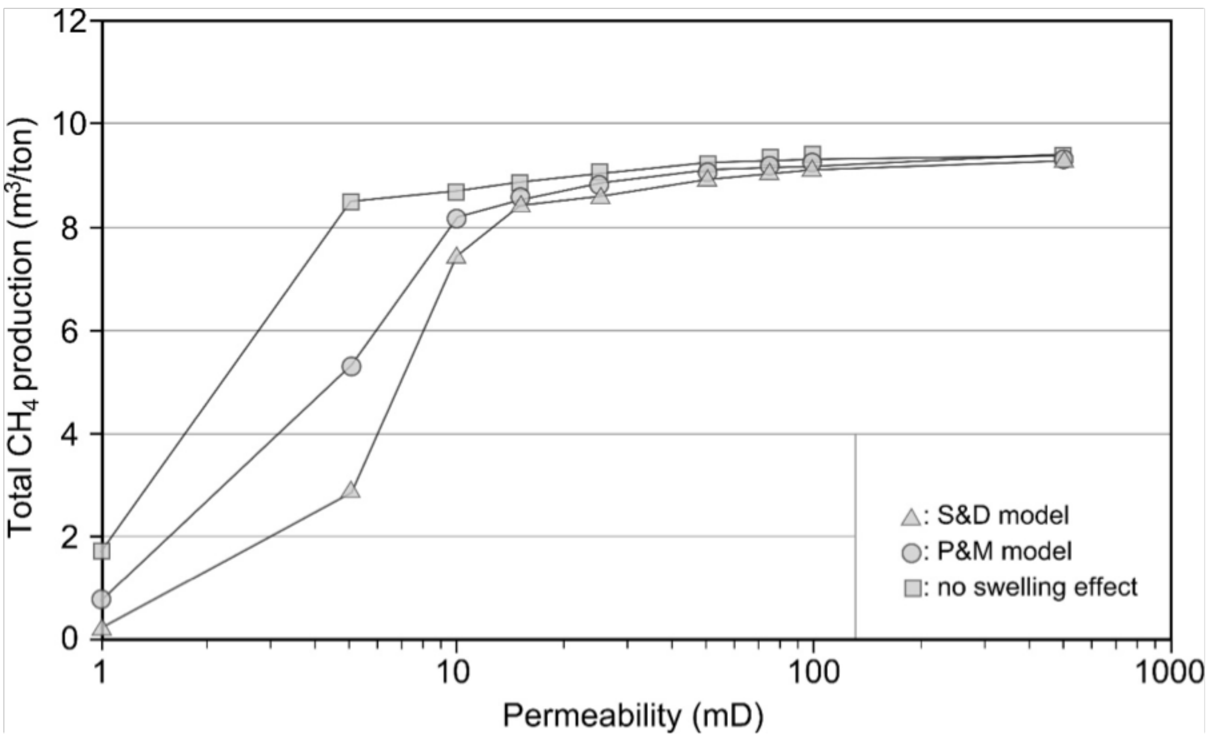

Figure 6: Total CH_4 production vs permeability.

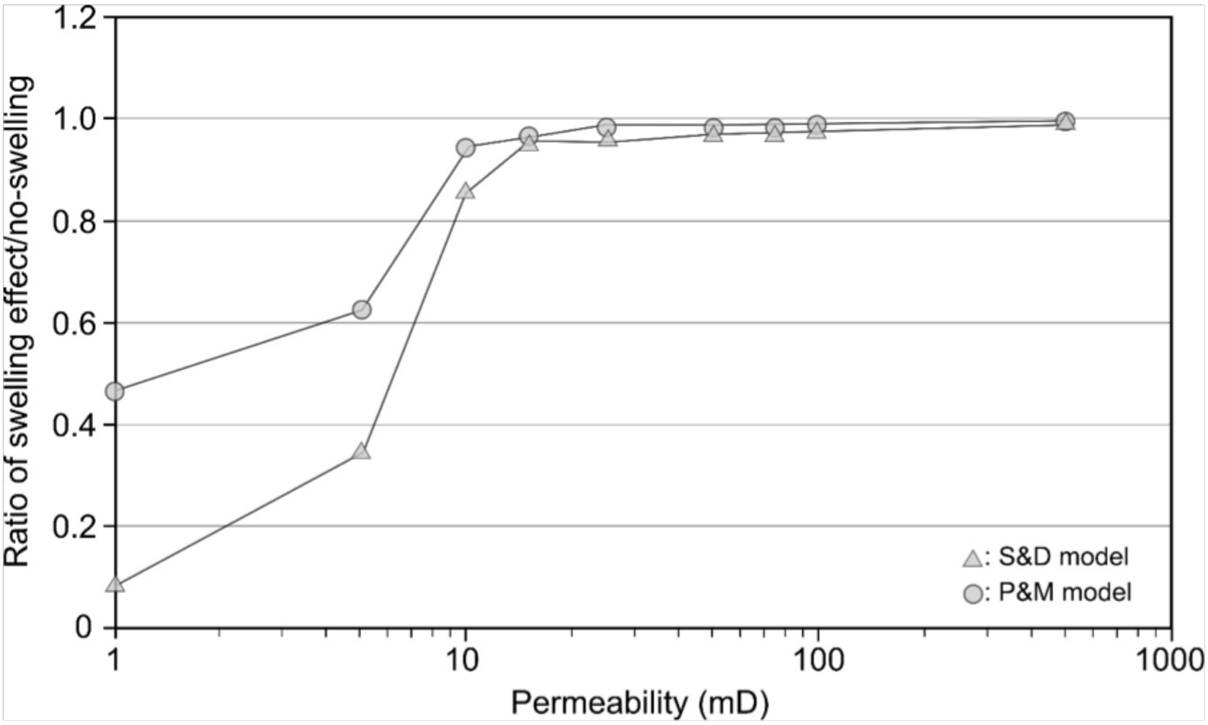

Figure 7: Total CH_4 production ratio of swelling effect/no-swelling.

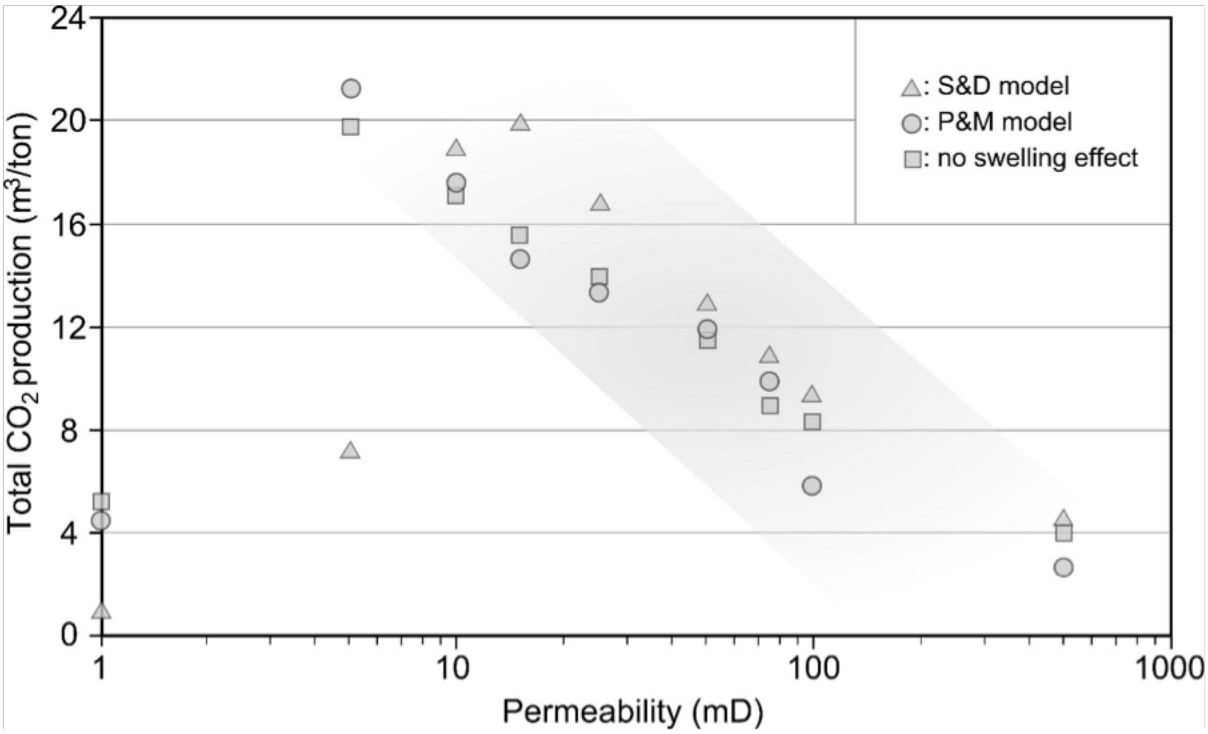

Figure 8: Total CO_2 injection vs time.

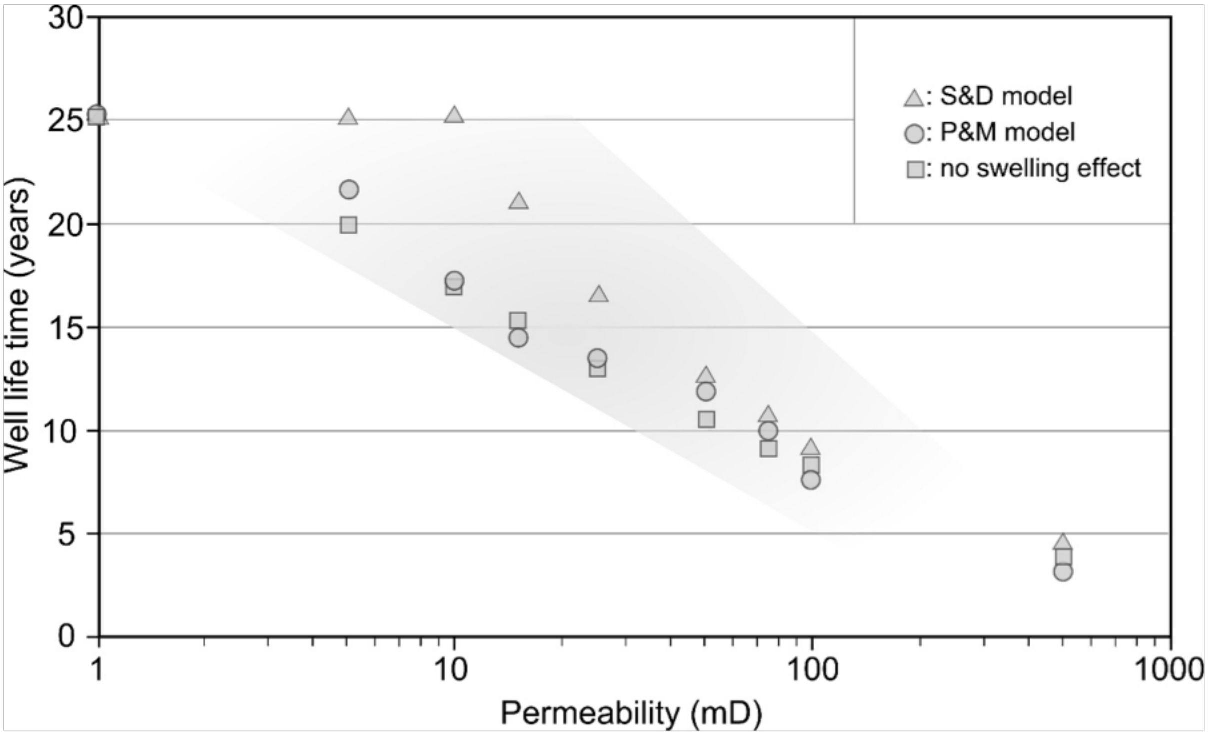

Figure 9: Well-life time vs permeability.

5 Summarizes

In general, CO_2-ECBMR makes increase of CH_4 production rate by 65%, from 48.80 to 74.40 m3 and store CO_2 up to 146.40×106 m^3 in the base case model. Based on the numerical simulation results, it can be summarized that swelling affects gas production at permeability 1 to 15 mD as the reported of coal permeability for low rank coal, however, it can be negligible at permeability over 15 mD. Thus, economic evaluation of CO_2-ECBMR could be conducted based on the numerical simulation presented in this study.

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