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Performance Assessment of CO_2 Sequestration in a Horizontal Well for Enhanced Coalbed Methane Recovery in Deep Unmineable Coal Seams

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Although the CO_2 injection for enhanced coalbed methane (ECBM) recovery is one of the potential coalbed methane production techniques, the effectiveness of the process is greatly dependent on the coal seam and method for CO_2 injectivity enhancement which is still becomes one of the technical challenges. This study has therefore aimed to investigate the performance of CO_2 sequestration for ECBM recovery through a horizontal well in deep unmineable coal seams. To achieve the objectives, a novel 3D numerical model was developed based on the characteristics of coal seams in Indonesia's Basins and reservoir simulation study was performed. From the results, the productivity of methane was increased by applying horizontal well instead of vertical well, especially for the coal seams with low permeability. In addition, CO_2 sequestration coupled with the use of a horizontal well resulted in the volume of CO_2 stored in deep unmineable coal seams increases to three times larger than a vertical well, it depends on the horizontal well length.

1. Introduction

Sequestration of carbon dioxide (CO_2) in coal seams is benefit to mitigate greenhouse gas emissions and enhanced coalbed methane (ECBM) recovery. For the purpose of CO_2 emission reduction, CO_2 must be stored in coal permanently, the coal seams used for storing CO_2 should be unmineable forever, otherwise, coal mining, combustion, or gasification would release CO_2 stored in the coal (Li and Fang, 2014). Thus, unmineable coal seams have the potential to store large volume of CO_2 (Corum et al., 2013). DOE's Midwest Geological Sequestration Consortium (MGSC) defines unmineable coal: all coals at 152-305 m deep, coal seams 0.5-1.1 m thick and so are reasonable sequestration targets (NETL, 2010).

At present, CO_2 sequestration for the ECBM recovery (CO_2-ECBM) has been studied to minimize the CO_2 release into the atmosphere, and these projects have been operating all over the world, such as the Fenn-Big Valley project in Canada, with two wells using a "huff and puff" scheme (Gunter et al., 2004), Yubari project in Japan, with a vertical injection well and a producing well (Fujioka et al., 2008). Although the ECBM recovery process is one of the potential coalbed methane (CBM) production enhancement techniques, the method for CO_2 injectivity enhancement is still become one of the technical challenge. Horizontal well may be an effective way to increase CO_2 injectivity compared with conventional vertical wells (Li and Fang, 2014). However, there is no study performed in assessing the effectiveness of the horizontal well for CO_2-ECBM, especially in deep unmineable coal seams.

This study has therefore aimed to investigate the performance of CO_2 sequestration for ECBM recovery through a horizontal well as the CO_2 injectivity enhancing technology in deep unmineable coal seams. In addition, the comparison on production performance of vertical and horizontal wells during ECBM will be examined and analysed by varying the well spacing. Furthermore, an optimization of horizontal well for CO_2-ECBM will be carried out by optimizing the well spacing and length of horizontal section. Finally, a sensitivity analysis will be

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conducted to evaluate the production performance of CO_2-ECBM in a horizontal well based on the different reservoir parameter of the coal seams.

2. Methodology

A numerical modelling simulation was used to model the coalbed methane reservoir using Generalized Equation of State Model-Computer Modeling Group (GEM-CMG) compositional simulator. Modelling developed by combining all of supporting data in terms of geology and reservoir, then the next step is to conduct the initialization to validate the reservoir model. Having obtained the valid model, the CO_2 storage capacity is estimated and a horizontal well is then designed and modelled to produce coalbed methane with the primary recovery method. Afterwards, the CO_2 injector wells (vertical and horizontal wells) are designed and modelled to inject CO_2 for the ECBM recovery. Subsequently, the comparison of primary CBM production and ECBM methods is analysed by performing production forecasting for 30 y. A sensitivity study is then conducted in order to examine and analyse the performance of CO_2-ECBM through vertical and horizontal injector wells by varying the well spacing. This is followed by an optimization of horizontal well for CO_2-ECBM by varying CO_2 injection scenario which are well-spacing between well producer and well injector and length of horizontal section of the injector well. The CBM production performance resulted from several scenarios will be compared and analysed for looking the optimum production and the optimum CO_2 injection model is then determined. Having determined the CO_2 injection model, a parametric study on the numerical model is conducted to assess the production performance based on a wide range of reservoir parameter of the coal seams. To understand the methodology, Figure 1 shows the study workflow.

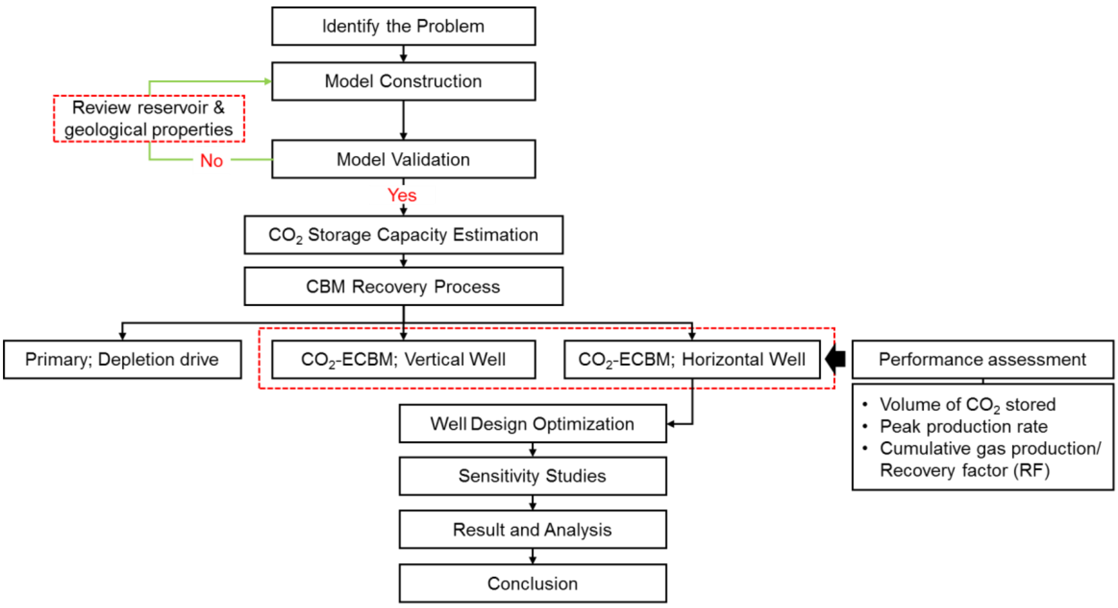

Figure 1: The study workflow

3. Model Development

A 24 x 23 x 6 (3312 grid) model which covers 670 acres of unmineable coal seams lying ± 1,050 m below the ground surface with total thickness of 6 m was considered for the model development. The model parameters used in this study based on the coal seams characteristic in South Sumatera Basin (Steven and Hadiyanto, 2004), Barito Basin (Sapiie et al., 2014) and Kutai Basin (Apriyani et al., 2014), Indonesia. Storage and compositional properties (Sosrowidjojo, 2013) and gas composition (Mazumder et al., 2010) from CBM wells in South Sumatera Basin were also considered during model construction. Having constructed a novel 3D numerical model, the model was then validated by initializing the results of GIP with volumetric method and initial reservoir pressure (Pi) from model with actual pressure data. The GIP resulted from model is about 240.76 MMm^3 while GIP from volumetric computation is estimated about 235.38 MMm^3, thus, the differences of about 2.35 %. Furthermore, initial reservoir pressure at reference depth of 1,051 m resulted from model is about 10,700 KPa, it has differences of about 1.90 % from actual pressure data (10,500 KPa at 1,051 m). The difference of IGIP between volumetric and simulator model as well as Pi between actual pressure data and simulator model below 5 % are considered good match and acceptable in the reservoir engineering practice. Therefore, the developed CBM reservoir model is valid and it is then used to estimate the CO_2 storage capacity. According to the results of the model, the total CO_2 sequestration capacity is estimated of about 222.86 MMm^3.

4. Coalbed Methane (CBM) Recovery Process

4.1 Comparison of Primary CBM and Enhanced CBM Recovery

Primary methane (CH_4) production capacity from the unmineable coal seams was examined using a horizontal well with length of horizontal section of 560 m during 30 y of simulation. The CH_4 production performance from primary production was then analysed and compared to the CO_2-ECBM technique. For CO_2-ECBM purposes, vertical and horizontal injector wells were modelled with the well-spacing between CBM producer and CO_2 injector of about 140 m. The horizontal well has length of horizontal section of 280 m. The CO_2-ECBM technique was examined by injecting CO_2 into the coal seams at maximum of 15,000 kPa injection pressure and injection rate of 10,000 m^3/d.

According to the production simulation results from 2016 until 2046 (Figure 2), total cumulative CH_4 production with primary CBM production is about 129.04 MMm^3 with recovery factor of 53.6 %. While simulation results of CO_2-ECBM, the model forecast showed that total cumulative CH_4 production with the vertical well injector of 149.85 MMm^3 with recovery factor of 62.23 % and the horizontal well injector resulted in 202.96 MMm^3 of cumulative CH_4 production with recovery factor of 84.30 %. The simulation results for each CBM recovery method is summarized in Table 1. From the results, application of CO_2 sequestration in a vertical well for ECBM can obtain additional recovery factor of about 8.63 % while through a horizontal well can achieve additional recovery factor of about 30.7 % with total incremental reserves compared to primary production of about 73.92 MMm^3. In addition, by applying a horizontal well for CO_2-ECBM can result in the total CO_2 stored in the coal seams increases to three times larger than a vertical well. It further will be examined and analyzed by varying the well spacing and horizontal well length in the next chapter.

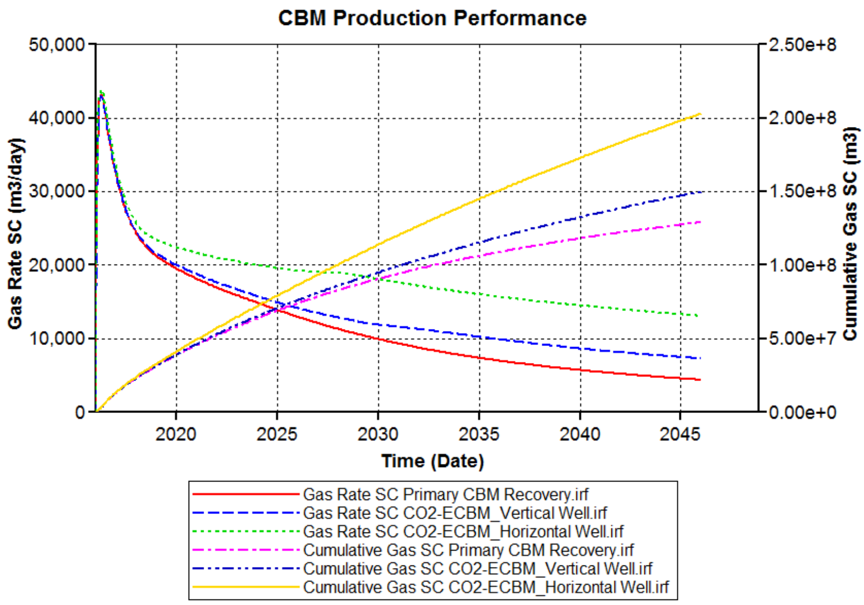

Figure 2: The comparison of production performance of Primary CBM and CO2-ECBM Recovery

Table 1: Summary of the simulation results for each CBM Recovery Method

Production Method	Volume of CO_2 Stored (MMm^3)	Peak Methane Production Rate (Mm^3/d)	30 Years Cumulative CH_4 Production (MMm^3)	30 Years Recovery Factor (%)
Primary	No injection	43.13	129.04	53.60
CO_2-ECBM (Vertical Well)	30.81	43.02	149.85	62.23
CO_2-ECBM (Horizontal Well)	93.11	43.90	202.96	84.30

4.2 Vertical and Horizontal Wells Performance in CO2-ECBM Recovery Process

A sensitivity study was performed in order to examine and analyse the performance of CO_2-ECBM through vertical and horizontal wells by varying the well spacing between CBM producer and CO_2 injector wells (70 m, 140 m, 210 m, 350 m, and 490 m). The simulation results of production performance and volume of CO_2 stored were observed and analysed in order to compare both of vertical and horizontal wells performance for different well spacings. Table 2 summarizes the simulation results for vertical well performance. From the results, it was observed that the volume of CO_2 stored in unmineable coal seams for a period of 30 y was increased from 23 MMm^3 to 55.20 MMm^3 when the well spacing was increased from 70 m to 490 m. The maximum cumulative CH_4 production was achieved for the well spacing of 350 m with recovery factor of about 63.83 %. For the horizontal well (length of horizontal section of 280 m), it is observed that decreasing well spacing from 490 m to 70 m increases the cumulative CH_4 production for 30 y from 184.73 MMm^3 to 205.98 MMm^3 (Table 3). The well spacing of 70 m resulted in the largest cumulative CH_4 production with recovery factor of 85.56 % while storing the smallest volume of CO_2 in unmineable coal seams which is 88.68 MMm^3.

Table 2: Summary of the simulation results for each well spacing of the vertical well

Well Spacing (m)	Volume of CO_2 Stored (MMm^3)	Peak Methane Production Rate (Mm^3/d)	30 Years Cumulative CH_4 Production (MMm^3)	30 Years Recovery Factor (%)
70 m	23.00	43.33	147.48	61.26
140 m	30.81	43.02	149.85	62.24
210 m	39.30	43.26	152.75	63.44
350 m	50.12	44.70	153.67	63.83
490 m	55.20	43.65	150.63	62.56

Table 3: Summary of the simulation results for each well spacing of the horizontal well

Well Spacing (m)	Volume of CO_2 Stored (MMm^3)	Peak Methane Production Rate (Mm^3/d)	30 Years Cumulative CH_4 Production (MMm^3)	30 Years Recovery Factor (%)
70 m	88.68	44.25	205.98	85.56
140 m	93.11	43.90	202.96	84.30
210 m	99.25	44.48	201.61	83.74
350 m	105.21	46.73	194.23	80.67
490 m	107.14	45.17	184.73	76.73

4.3 Optimization of Horizontal Well for CO2-ECBM Recovery

An optimization of CO_2 sequestration in a horizontal well for ECBM was carried out by varying length of horizontal section. In the sensitivity study of horizontal well length, the selected 70 m well spacing was investigated by varying lateral length from 210 m to 560 m. Volume of CO_2 stored and production performance of 30 y for each case are summarized in Table 4. The results of methane production rate and cumulative production obtained from the simulation for each length are plotted in Figure 3. It is also note that the vertical length (surface to the starting point of horizontal) of each horizontal well is constant. It is observed that increasing length of horizontal well from 210 m to 560 m increases the cumulative CH_4 production for 30 y from 195.16 MMm^3 to 219.23 MMm^3. In addition, volume of CO_2 stored in the coal seams also increases from 76.83 MMm^3 to 104.23 MMm^3.

Table 4: Summary of the simulation results for each horizontal well length

Horizontal Well Length (m)	Volume of CO_2 Stored (MMm^3)	Peak Methane Production Rate (Mm^3/d)	30 Years Cumulative CH_4 Production (MMm^3)	30 Years Recovery Factor (%)
210 m	76.83	43.94	195.16	81.06
280 m	88.68	44.22	205.98	85.56
350 m	95.77	44.52	212.52	88.27
420 m	100.27	44.80	216.55	89.94
490 m	102.80	45.19	218.57	90.78
560 m	104.23	45.24	219.23	91.06

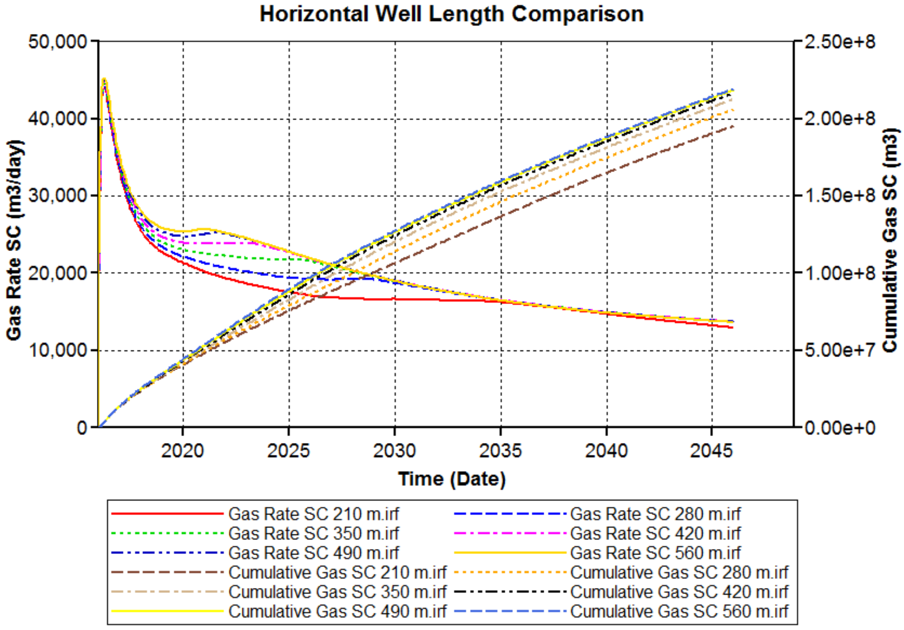

Figure 3: Production performance of various horizontal well lengths

4.4 Sensitivity Analysis

A sensitivity analysis was carried out to examine the influences of different reservoir parameter on the numerical model in order to assess the performance of CO_2-ECBM. The 'High', 'Low' and 'Base' cases were designed for the value of each uncertain parameter, which were quantified through the sensitivity analysis. In this analysis, the infuences of the reservoir condition on cumulative methane production for the CO_2 sequestration in a horizontal well (well spacing 70 m and length of horizontal section 560 m) was investigated using the values of each parameter assisgned from 'High', 'Low' and 'Base' cases. The values assisgned in each case are summarized in Table 5.

Table 5: Parameter used in sensitivity analysis

Reservoir Parameter	Low Case	Base Case	High Case
Fracture permeability (mD)	2	4	6
Matrix permeability (mD)	0.1	1	4
Reservoir temperature (°C)	35	40	45
Skin Factor	+2	0	-2

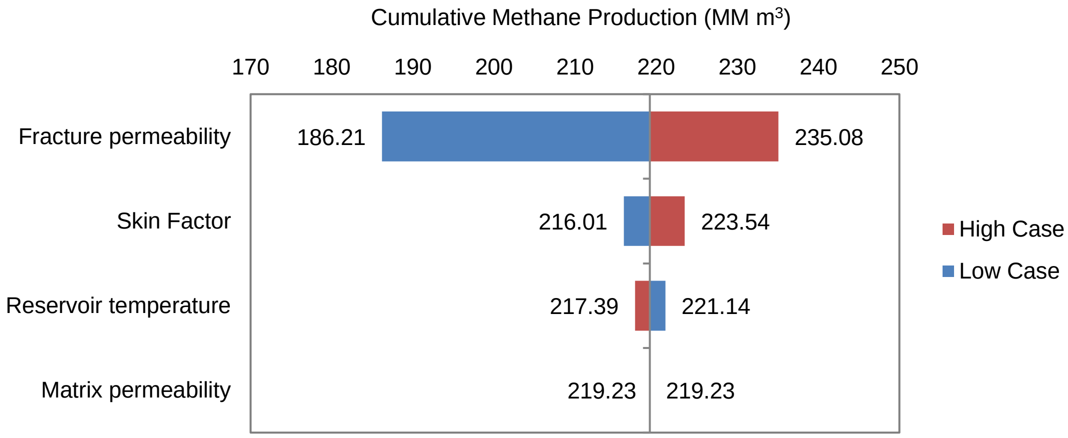

Figure 4: Tornado plot indicating the influences of reservoir parameters on cumulative CH_4 production

The results of sensitivity analysis is presented in the tornado plot in order to show the comparison of the sensitivities of each parameter. Figure 4 shows the results obtained from this sensitivity analysis which orderly indicates the impact of each parameter on cumulative methane production. The axis in the middle of this graph represents the base case selected for the study which has a cumulative CH_4 production of 219.23 MMm^3. As shown in the tornado chart, fracture permeability is plotted on the top since it has the most significant effect on methane production. It is followed by skin factor and reservoir temperature of the coal seams which are also influential parameters on methane recovery. However, there is no effect of matrix permeability on methane production.

5. Conclusions

Through the numerical simulation study which assesses the performance of CO_2 sequestration for ECBM in deep unmineable coal seams, it has proven that the productivity of methane was increased by applying horizontal well instead of vertical well, especially for the coal seams with low permeability. In addition, CO_2 sequestration coupled with the use of a horizontal well could result in the volume of CO_2 stored in deep unmineable coal seams increases to three times larger than a vertical well, it depends on the horizontal well length. From the results of sensitivity analysis, fracture permeability and skin factor have a significant impact on methane production and it therefore these parameters should be considered on application of horizontal well for CO_2-ECBM recovery process in unmineable coal seams.

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