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Screening Criteria of Optimum Carbon Dioxide Injection for Enhanced Coalbed Methane Recovery and Prediction of Carbon Dioxide Storage Capacity: A Case Study in South Sumatera Basin, Indonesia

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This study proposes the screening criteria for optimum CO_2 injection to enhanced coalbed methane (ECBM) recovery as well as predicting CO_2 storage capacity by developing a novel numerical model based on the characteristic of coal seams and CBM field in South Sumatera Basin, Indonesia. The comparison of primary and enhanced CBM recovery was analysed by performing production forecasting for 30 y of simulation. A sensitivity study was then conducted in order to examine the performance of ECBM under the influences of CBM reservoir properties which are fracture permeability, matrix porosity, reservoir temperature, and coal seam depth. In summary, the reservoir screening criteria for successful application of CO_2-ECBM have been fully defined and proposed. The key criteria of reservoir characteristics for successful application of CO_2-ECBM are likely to be homogeneous reservoir, simple structure, fracture permeability more than 2 mD, matrix porosity more than 0.5 %, reservoir temperature less than 100 °C, and coal seam depth more than 500 m. Furthermore, the method for estimating CO_2 storage capacity in coal seams has been proposed by simplifying the Original Gas in Place (OGIP) volumetric computation which is validated with the numerical model through sensitivity studies. The proposed equation is applicable for 100 % gas saturation in coal matrix and adsorption process as the main and the only storage mechanism in coal seams.

1. Introduction

Indonesia has the highest carbon dioxide (CO_2) emissions rate among the Southeast Asian region and the tenth largest CO_2 emitting country in the world with 611.4 Mt CO_2 emissions in 2015 (BP, 2016). Carbon Capture Storage (CCS) provide an opportunity for the government of Indonesia's goal of improved energy supply and security, while also reducing CO_2 emissions. Studies regarding to CCS in Indonesia have been conducted since 2003 and the first CCS project was started in 2012 at the Gundih Gas Field in Central Java, Indonesia. According to LEMIGAS (2015), South Sumatera Basin is the third most suitable sedimentary basins for CO_2 storage due to well characterised reservoirs, favourable and well-known geological structure, and there is potential to reuse existing infrastructure. South Sumatera power plant is well placed to take advantage of enhanced oil recovery (EOR) opportunities (World Bank, 2015). The current studies regarding to CO_2 storage in South Sumatera are focusing in depleted oil and gas reservoirs. However, coal seams have good potential for CO_2 storage while enhancing coal seam gas recovery.

Sequestration of 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, otherwise, coal mining, combustion, or gasification would release CO_2 stored in the coal (Li and Fang, 2014). Coal that is considered unmineable because of geologic, technological, and economic factors (typically too deep, too thin, or lacking the internal continuity to be economically mined with today's technologies) may have potential for CO_2 storage (U.S. DOE, 2012).

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At present, CO_2 sequestration for the ECBM recovery (CO_2-ECBM) has been studied to minimise 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). From engineering aspect, reservoir screening criteria are essential for locating favourable areas for successful application of CO_2-ECBM, however, these criteria have not yet been fully defined. As stated by Li and Fang (2014), successful injection of CO_2 into coal seams requires sufficient permeability along pores and fractures, but it has not yet been defined clearly. The key criteria of reservoir characteristics are extremely important for successful application of CO_2-ECBM technique and it should be defined clearly.
Although the ECBM recovery process is one of the potential coalbed methane (CBM) production enhancement techniques, the effectiveness of the process is greatly dependent on the coal seam characteristics. Estimation of CO_2 storage capacity is highly important for further consideration in optimisation of CO_2 sequestration. This study aimed to propose the reservoir screening criteria for optimum CO_2 sequestration for ECBM as well as predict the CO_2 storage capacity in a case study in South Sumatera Basin, Indonesia. To achieve the objectives, a novel three-dimensional (3D) numerical model was developed based on the characteristics of coal seams in South Sumatera Basin, Indonesia and reservoir simulation study and analysis were performed.

2. Methodology

A numerical modelling simulation was used to model the coalbed methane reservoir using Generalised Equation of State Model-Computer Modelling 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 initialisation to validate the reservoir model. In this process, the Gas in Place (GIP) resulted from the model was compared with volumetric computational method and initial reservoir pressure from the model was compared with actual pressure data. The reservoir pressure was derived from hydrostatic pressure calculation as function of coal seam depth. The standard volumetric computation for estimating Original Gas in Place or OGIP (Stevens and Hadiyanto, 2004) is shown in Eq(1):

$$\text{OGIP} = \{\text{Coal thickness, m} \times (1 - \text{ash content, frac}) \times (1 - \text{moisture content, frac}) \times \text{coal density, kg/m}^3 \times (1 - CO_2 \text{ content, frac}) \times CH_4 \text{ content, m}^3\text{/kg} \times \text{Prospective area, m}^2\} \quad (1)$$

Having obtained the valid model, a vertical well was then designed and modelled to produce coalbed methane with the primary recovery. A vertical CO_2 injector well was designed and modelled to inject CO_2 for the ECBM recovery. Source of CO_2 was considered comes from Merbau Gas Gathering Station (GGS) based on LEMIGAS study (LEMIGAS, 2015). Subsequently, the comparison of primary CBM production and ECBM methods was analysed by performing production forecasting for 30 y. A sensitivity study was then conducted in order to examine the performance of ECBM under the influences of CBM reservoir properties which are permeability, porosity, reservoir temperature, coal seam depth (related to hydrostatic pressure). Having performed the sensitivity analysis, the reservoir screening criteria for successful application of CO_2-ECBM in a vertical well was then proposed and defined. CO_2 storage capacity in coal seams was predicted using the proposed equation and validated with the numerical model through sensitivity studies.

3. Results and Discussion

3.1 Model Development

A cartesian grid with 21 x 21 x 3 (1,323 grid) model which covers 1.1 km^2 of unmineable coal seams lying ± 760 m below the ground surface with total thickness of 25 m was considered for the model development. The model parameters used in this study based on the coal seams characteristics in South Sumatera Basin, Indonesia (Stevens and Hadiyanto, 2004). 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. The novel model constructed has coal seams laterally continuous (Bowe and Moore, 2015) and the geological structure is simple (CBMA, 2013), there is no fault neither fold in the model. Figure 1 shows the coal seams model constructed for the simulation study.
Having constructed a novel 3D numerical model, the model was then validated by initialising the results of Gas in Place with volumetric computation method and initial reservoir pressure from model with actual pressure data. The GIP resulted from model is about 224.15 MMm^3 while GIP from volumetric computation is estimated about 205.09 MMm^3, the differences of about 9.22 %. Initial reservoir pressure at reference depth of 760 m resulted from model is about 7,576.2 kPa, the differences of about 1.65 % from actual pressure data (7,453.05 kPa at 760 m). According to these results, the differences of both parameters below 10 % are considered

good match and acceptable in reservoir engineering practice. The developed CBM reservoir model is valid and it is then applicable to perform reservoir simulation study.

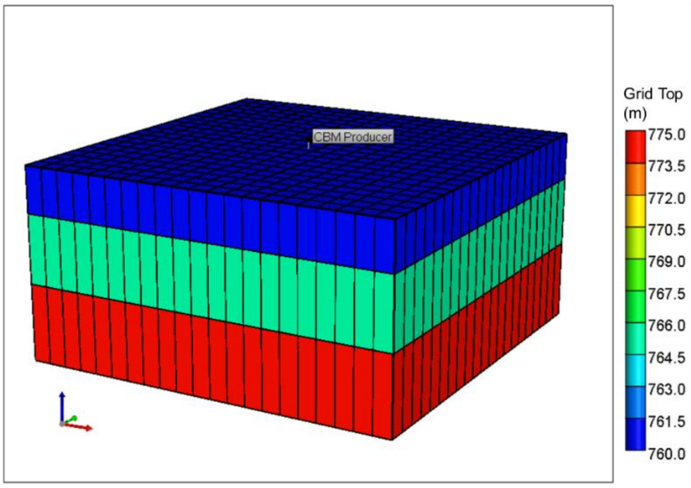

Figure 1: The CBM model constructed for simulation study

3.2 Sensitivity Analysis

Primary methane (CH_4) production capacity from the coal seams was examined using a vertical well which is perforated in all of coal layers 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, a vertical CO_2 injector well was modelled with the well-spacing between CBM producer and CO_2 injector of about 200 m. The CO_2-ECBM technique was examined by injecting CO_2 into the coal seams at maximum of 10,000 kPa injection pressure and injection rate of 10,000 m^3/d. According to the production simulation results from 2016 until 2046 (Table 1), total cumulative CH_4 production with primary CBM production is about 134.41 MMm^3 with recovery factor of 59.96 %. With simulation results of CO_2-ECBM, the model forecast showed total cumulative CH_4 production with the vertical well injector of 174.02 MMm^3 and recovery factor of 77.64 %. From the results, application of CO_2 sequestration in a vertical well for ECBM can obtain additional recovery factor of about 1.3 times the primary recovery method (base case).

Having performed CO_2-ECBM technique, 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 recovery factor (RF) obtained from the model was examined under the influences of fracture permeability, matrix porosity, reservoir temperature and coal seam depth which is also represented the hydrostatic pressure. The additional recovery factor (ARF) was then calculated and plotted to see and analyse the influences of different reservoir parameter to the RF addition. Figure 2 shows the results of sensitivity studies on the influences of fracture permeability, matrix porosity, temperature, and coal seams depth on RF addition. From the results, more fracture permeability will result in more additional recovery factor. This is also proportional with increasing matrix porosity and coal seam depth as well as hydrostatic pressure will increase additional recovery factor. Increase of reservoir temperature will result in less of additional recovery factor. This may be caused by the gas sorption capacity (GSC) tends to decrease with increasing temperature, and consequently reduces CH_4 production.

Table 1: Summary of the simulation results of Primary and Enhanced CBM Recovery Methods

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	24.57	134.41	59.96
CO_2-ECBM	109.55	27.58	174.02	77.64

Based on the results of model development and sensitivity studies, the reservoir screening criteria for successful application of CO_2-ECBM was then proposed. The key criteria are likely to be:

Homogeneous reservoir: The coal seam reservoir(s) should be laterally continuous in terms of the reservoir homogeneity. This ensures the lateral sweep efficiency of injectant through the reservoir and the volume of CO_2 stored in coal seams will be optimum as well.

Simple structure: The geological structure of the reservoir should be simple in terms of minimally faulted and folded. The faults may divert injectant away from the reservoir, reducing the efficiency of sequestration and enhanced recovery. Structurally complex areas frequently have damaged coal properties in particularly fracture permeability become lower.
Fracture permeability: The coal seam reservoir(s) should have fracture permeability more than 2 mD. The injection flow rate through the reservoir is proportional to the fracture permeability. High flow rate will result in high efficiency of sequestration and enhanced recovery. Thus, sufficient permeability along fractures is highly required for successful sequestering CO_2 in coal seams.
Matrix porosity: The matrix porosity of coal seam reservoir(s) should be more than 0.5 %. More matrix porosity will result in more adsorption capacity which lead to affect more additional recovery factor due to volume of CO_2 will be stored in matrix porosity. Higher matrix porosity ensures the optimum or efficiency of CO_2 sequestration and enhanced coalbed methane recovery.
Reservoir temperature: The temperature of coal seam reservoir(s) should be less than 100 °C due to the gas sorption capacity tends to decrease with increasing temperature which leads to affect decrease of the efficiency of CO_2-ECBM.
Depth: Coal seam depth should be more than 500 m. The gas sorption capacity increases with increasing pressure which is a function of coal seam depth. Thus, increase of coal seam depth will increase reservoir pressure which in turn leads to an increase of GSC which ensures the efficiency of CO_2-ECBM.

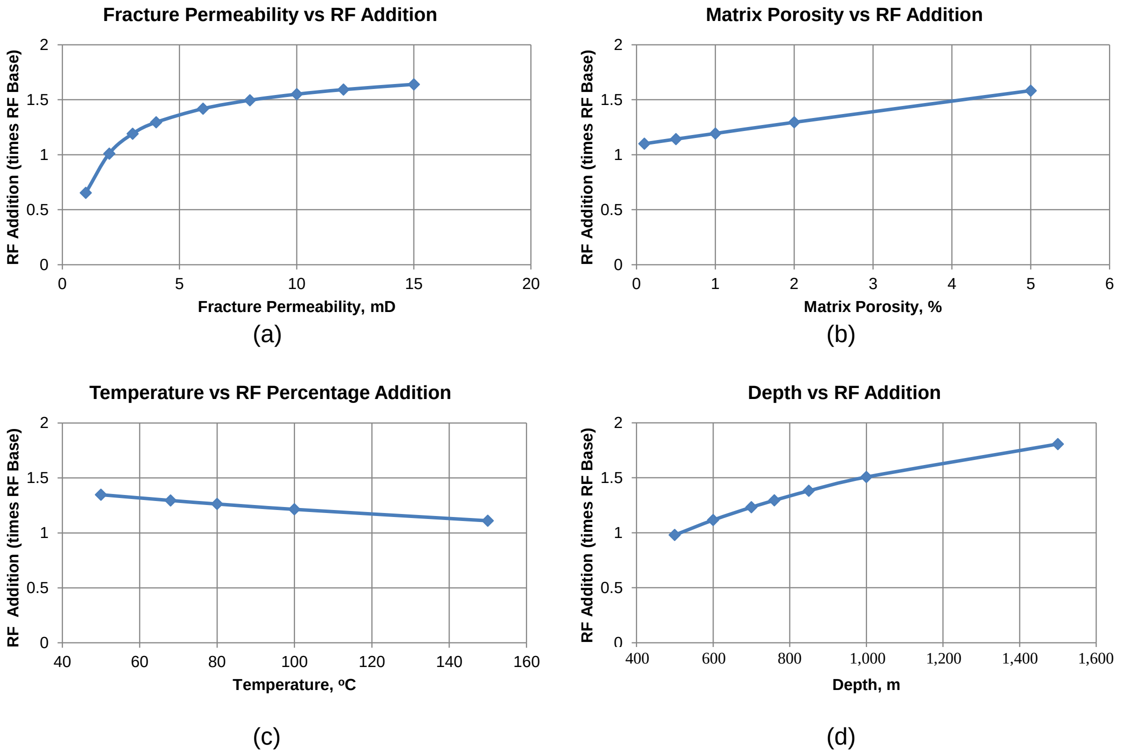

Figure 2: Sensitivity studies on the influences of different reservoir parameter on additional recovery factor obtained from CO_2 injection compared to primary recovery method (base case); (a) fracture permeability vs RF addition, (b) matrix porosity vs RF addition, (c) temperature vs RF addition, (d) depth vs RF addition

3.3 Prediction of CO_2 Sequestration Capacity

Carbon dioxide can be stored in coal by sorption and diffusion. In unmineable coal seams, adsorption trapping is the main sequestration method. The process of adsorption causes the CO_2 to bond to the coal causing the CO_2 to be physically and permanently trapped on the coal provided sufficient pressure is maintained. Two assumptions have been made in order to simplify the calculation based on the volumetric Original Gas In Place (OGIP) method; there is no water saturation in the coal matrix and no gas saturation in the coal fracture (Sw matrix = 0 and Sg fracture = 0), and adsorption trapping is the main sequestration method in coal seams, which was considered as the only storage mechanism in this study. By simplifying the OGIP volumetric calculation, the CO_2 adsorption capacity in the coal seams can be calculated using Eq(2):

$$CO_2 \text{ storage capacity} = \rho_{CO2} \times A \times h \times \rho_b \times G_{CS} \quad (2)$$

Where ρ_{CO2} = 1.873 kg/m^3, A = 1,102,500 m^2, h = 25 m, ρ_b = 1459.27 kg/m^3, G_{CS} = 0.007 m^3/kg, CO_2 storage capacity = 413.9 x 10^6 kg. The CO_2 storage capacity resulted from the proposed equation was then compared with the numerical model through sensitivity analysis. It is important to perform a parametric study to address the uncertainty of the parameters input to the CO_2 storage capacity and improves the results of prediction. The 'High', 'Low' and 'Base' cases were designed for the value of each uncertain parameter, which were quantified through the sensitivity analysis. The values assigned in each case are summarised in Table 2.

Table 2: Parameter used in sensitivity analysis

Reservoir Parameter	Low Case	Base Case	High Case
Prospective area, m^2	640,000	1,102,500	1,690,000
Coal seams thickness, m	12.5	25	37
Coal density, kg/m^3	1,300	1,459.27	1,500
Gas sorption capacity, m^3/kg	0.0025	0.007	-

The results of CO_2 storage capacity for each methods and sensitivity studies are presented in the tornado plot in order to show the comparison of the sensitivities of each parameter. Figure 3 and 4 show CO_2 storage capacity resulted from the simplified OGIP computation and numerical simulation, respectively. The error obtained for each case was calculated. The average error for 'High' case of 7.53 %, 'Low' case of 7.68 % and 'Base' case of 7.62 %. In average, the total error resulted is about 7.61 %. Thus, the error resulted from the simplified OGIP computation or proposed method is not too significant or less than 10 %, consequently, it can be used and applicable to estimate the CO_2 storage capacity in coal seams. In addition, gas sorption capacity, coal thickness and prospective area prove to be the parameter with large impact on CO_2 storage capacity. These parameters are required to be precisely estimated to improve accuracy of the prediction.

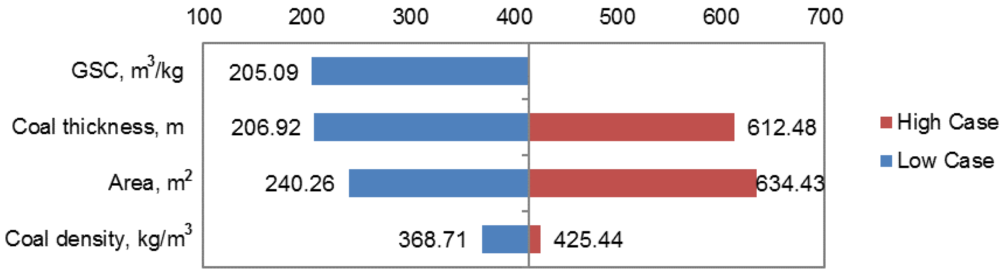

Figure 3: Tornado plot indicating the influences of different reservoir parameter on CO_2 storage capacity resulted from the simplified OGIP computation (proposed equation)

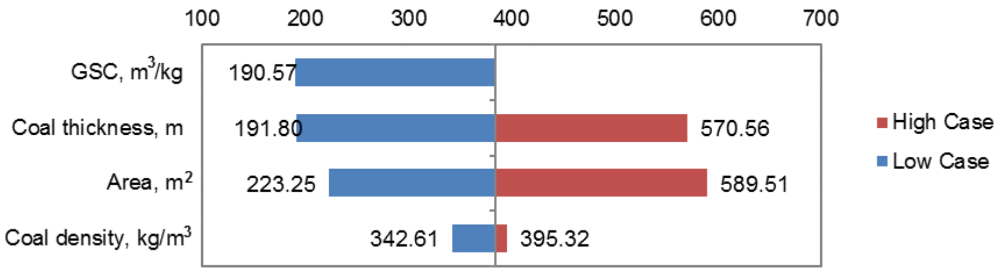

Figure 4: Tornado plot indicating the influences of different reservoir parameter on CO_2 storage capacity resulted from numerical simulation

4. Conclusions

A novel numerical model was developed based on the characteristics of coal seams in South Sumatera Basin, Indonesia. Based on the results of model development and sensitivity studies, the reservoir screening criteria for successful application of CO_2 sequestration for enhanced coalbed methane (CO_2-ECBM) recovery have been fully defined. The proposed key criteria are likely to be homogeneous reservoir, simple structure (minimally faulted and folded), fracture permeability more than 2 mD, matrix porosity more than 0.5 %, reservoir temperature less than 100 °C, and coal seam depth more than 500 m.

Furthermore, the method for estimating CO_2 storage capacity in coal seams has been successfully proposed by simplifying the Original Gas in Place (OGIP) volumetric computation. The proposed equation is applicable for 100 % gas saturation in coal matrix and adsorption process as the main and the only storage mechanism in coal seams. The proposed equation to estimate CO_2 storage capacity in coal seam(s) is shown in Eq(3):

$$\text{CO}_2\text{ storage capacity} = \text{CO}_2\text{ density, kg/m}^3 \times \text{Prospective area, m}^2 \times \text{Coal seam(s) thickness, m} \times \text{Coal bulk density, kg/m}^3 \times \text{Gas sorption capacity, m}^3\text{/kg} \quad (3)$$

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