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ORIGINAL PAPER

Identification of coal seams suitability for carbon dioxide sequestration with enhanced coalbed methane recovery: a case study in South Sumatera Basin, Indonesia

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Abstract Sequestering carbon dioxide (CO_2) with enhanced coalbed methane recovery (ECBM) is a promising clean coal technology in Indonesia, which can reduce CO_2 emissions and potentially lower-cost alternative for fulfilling of future Indonesia's gas demand. Coal seams in South Sumatera Basin, Indonesia, are well placed to take advantage of CO_2 sequestration based on economical and regulatory criteria. From technical criteria assessment, there are very limited studies undertaken in this area, especially for identification of coal seams suitability for CO_2-ECBM in South Sumatera Basin. This study has therefore aimed to propose the technical criteria of coal seams suitability for CO_2-ECBM recovery as well as predicting CO_2 storage capacity by developing a novel numerical model based on the characteristics of coal seams in South Sumatera Basin. The comparison of primary and CO_2-ECBM recovery was analysed by performing production forecasting for 30 year of simulation. A sensitivity study was then conducted in order to examine the performance of CO_2-ECBM under the influences of permeability, a determining factor in the viability of a CO_2 storage in coal seams. A simplified method for estimating CO_2 storage capacity in coal seams has been proposed which was validated with the novel numerical model through parametric studies. From this study, one can screen the suitable coal seams for CO_2 storage with enhanced coalbed methane recovery and can quickly quantify the CO_2 storage capacity in the coal seams with general available data.

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Keywords South Sumatera Basin · CO_2-ECBM · CO_2 storage capacity · Novel numerical model

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 $MtCO_2$ emissions in 2015 (BP 2016). Carbon capture storage (CCS) provides 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-characterized reservoirs, favourable and well-known geological structure, and there is potential to reuse existing infrastructure. The current studies regarding to CO_2 storage in South Sumatera are focusing in depleted oil and gas reservoirs. Coal seams also have good potential for CO_2 storage while enhancing coal seam gas recovery.

Coalbed methane (CBM) resource in Indonesia is identified of 453.3 TCF, and the biggest CBM resources are located in South Sumatera Basin which is about 183 TCF or 40.37% of total Indonesia's CBM resource (Stevens and Hadiyanto 2004). With regard to the increase of gas demand significantly in Indonesia, CBM will be potentially lower-cost alternative for fulfilling of future Indonesia's gas demand. South Sumatera has large presence of the industrial and power sector which resulted in high-purity CO_2 content and large CO_2 volume per year (LEMIGAS 2015). The existing gas pipeline infrastructure can be used to accommodate the CO_2 captured from the CO_2 sources, as well as low cost CO_2 sources (World Bank 2015). Gas supply shortages in Sumatra and West Java could provide a strong regional market opportunity for CBM (Wood Mackenzie 2017). These conditions potentially make South Sumatera is well placed to take advantage of CO_2 sequestration opportunities. These facts encouraged the authors to conduct a comprehensive study on CO_2 sequestration with enhanced coalbed methane (CO_2-ECBM) recovery, especially in South Sumatera Basin.

The issue related to the environment impact due to discharging CO_2 has been increasing recently. As a result, many are looking to storage CO_2 as an approach to reduce the carbon impact of stationary point sources of CO_2 (Hasaneen et al. 2014). Sequestration of CO_2 into coal seams is beneficial to mitigate greenhouse gas emissions and enhanced coalbed methane recovery. For the purpose of CO_2 emission reduction, CO_2 has to be stored in the coal permanently, the coal seams should be unmineable forever for storing CO_2, otherwise, coal mining, combustion, or gasification would release CO_2 stored in the coal (Li and Fang 2014). Corum et al. (2013) mentioned that unmineable coal seams have the potential to store large volume of CO_2. 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).

At present, CO_2 sequestration for the ECBM recovery has been studied to minimize the CO_2 release into the atmosphere, and these projects have been operating all over the world. Referring to the injection methodology, several methods have been introduced and applied in order to inject CO_2 into coal seams, 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), APP CO_2-ECBM project in China, CO_2 was injected through multi-lateral horizontal well into coal seams (Pan 2012). From technical or reservoir engineering aspect, permeability is a determining factor in the viability of a CO_2 storage in coal seams (Bachu et al. 2007). Permeability is a dynamic reservoir parameter which influences fluid flow in the porous medium. The gas rate (Q_g) is mainly affected by permeability following Darcy's law. 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 been defined yet. Type and criteria of permeability which have large impact on the CO_2-ECBM performance should be understood due to the coalbed methane reservoir has dual permeability system, which are matrix and fracture permeability. The key criteria of reservoir characteristics are then 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 CBM production enhancement techniques, the effectiveness of the process is greatly dependent on the coal seam characteristics. The estimation of CO_2 storage capacity is highly important for further consideration in optimization of CO_2 sequestration. This study has therefore aimed to propose the identification of coal seams suitability for CO_2-ECBM in terms of the technical criteria with 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. Using numerical simulation, this paper presents the investigation of permeability effects on the performance of CO_2-ECBM and proposes a simplified method for estimating CO_2 storage capacity in coal seams. From this study, one can screen the ideal candidates for CO_2 sequestration with enhanced coalbed methane recovery and can quickly quantify the CO_2 storage capacity in the coal seams without performing numerical simulation.

Methods

Numerical reservoir simulation is the preferred tool to be applied in this study due to the CBM flow problem that depends on many pressure-dependent parameters which can affect the fluid behaviour and the reservoir performance (Giamminonni et al. 2010). Implementation of numerical simulation has successfully applied for CO_2 storage in saline aquifers in a field-scale study (Yang et al. 2012). A compositional numerical simulation was used to model the coalbed methane reservoir using Generalized Equation of State Model-Computer Modelling Group (GEM-CMG) compositional simulator. The simulator provides extended Langmuir isotherms to model the preferential adsorption of CO_2 and accurate early time water and methane production predictions. Modelling was developed by combining all of the supporting data in terms of geology and reservoir, and then the next step is to conduct the initialization process to validate the reservoir model. 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 a function of coal seam depth. The standard volumetric computation for estimating Original Gas in Place or OGIP (Stevens and Hadiyanto 2004) is shown below:

$$\mathrm{OGIP} = \left\{ \begin{array}{l} \text{Coal thickness, m} \times (1 - \text{ash content, frac}) \times (1 - \text{moisture content, frac}) \times \\ \text{coal density, kg/m}^3 \times (1 - \text{CO}_2\text{content, frac}) \times \text{CH}_4\text{content, m}^3/\text{kg} \times \text{Prospective area, m}^2 \end{array} \right\} \quad (1)$$

Having obtained the valid model, a vertical well was then designed and modelled to produce coalbed methane with the primary recovery. Afterwards, a vertical CO_2 injector well was designed and modelled to inject CO_2 for the ECBM recovery. A comparison of primary CBM production and ECBM methods was analysed by performing production forecasting for 30 year. A sensitivity study was then conducted in order to examine the performance of ECBM in terms of methane (CH_4) production recovery and CO_2 storage under the influences of reservoir permeability (k) which are fracture and matrix permeability. Having performed the sensitivity analysis, the reservoir criteria for successful application of CO_2-ECBM in a vertical well was then proposed and defined. With regard to CO_2 storage capacity in coal seams, it was predicted using the proposed equation and validated with the novel numerical model through sensitivity studies.

A cartesian grid with 21 × 21 × 3 (1323 grid) model which covers 1.1025 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 were 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), and there is no fault neither fold in the model. The reservoir properties used for construction of base case model are given in Table 1. The reservoir has 100% CH_4 saturation in the coal matrix while cleat or fracture porosity is saturated by 100% water. The reservoir was assumed homogenous where the permeability values are same in any direction (*i, j, k*) which of four (4) mD whether for matrix or fracture permeability. The reservoir was assumed as finite without driving mechanism from outside or only natural depletion drive was considered as the reservoir drive mechanism, and there was no skin found in the wellbore. 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 initializing 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 of about 224.15 MMm^3 while GIP from volumetric computation was estimated of about 205.09 MMm^3, it resulted in differences of about 9.22%. Initial reservoir pressure at reference depth of 760 m resulted from the model of about 7576.2 kPa, with the differences of about 1.65% from actual pressure data (7453.05 kPa at 760 m). According to these results, the differences of both parameters below 10% are considered

Table 1 Reservoir parameters used for construction of CBM reservoir model

Reservoir parameters	Dimension	Value
Surface area	m^2	1,102,500
Coal thickness	m	25
Rock density	kg/m^3	1459.27
Gas saturation	Fraction	0 (100% CH_4)
Water saturation	Fraction	1
Rock compressibility	1/kPa	2×10^{-5}
Matrix porosity	Fraction	0.02
Fracture porosity	Fraction	0.005
Matrix permeability (*i, j ,k*)	mD	4
Fracture permeability (*i, j ,k*)	mD	4
Reservoir temperature	°C	68
Datum depth	m	760
Initial pressure @datum	kPa	7453.05
Langmuir pressure	kPa	3500
Langmuir volume	m^3/t	7

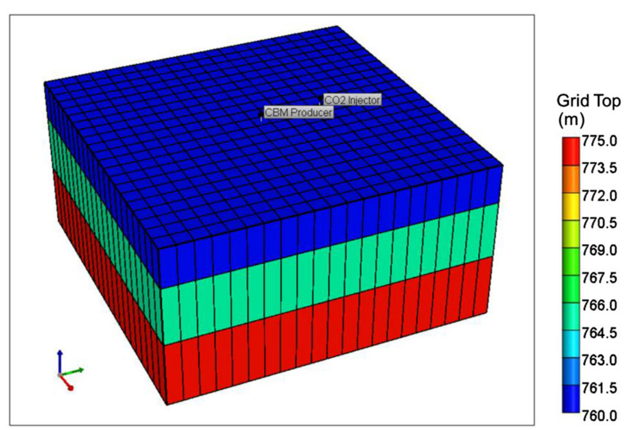

Fig. 1 CBM model constructed for simulation study

good match and acceptable in reservoir engineering practice. It can be inferred that the developed CBM reservoir model is valid, and it is then applicable to perform reservoir simulation study.

Primary methane production recovery from the coal seams was examined using a vertical well which was perforated in all of coal layers during 30 year of simulation. In primary recovery, CBM was produced by natural flow or known as depletion method. 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 the maximum of 10,000 kPa injection pressure and injection rate of 10,000 m^3/d. Source of CO_2 was considered comes from Merbau Gas Gathering Station (GGS) based on LEMIGAS study (2015). The CO_2 sources from the Merbau GGS contain high-purity CO_2 content where CO_2 absorber unit discharges about 363 t/d CO_2.

Results and discussion

Comparison of primary CBM and ECBM recovery

According to the production simulation results from 2016 until 2046 (Fig. 2), total cumulative CH_4 production with primary CBM production is about 36,882.3 t CH_4. With the simulation results of CO_2-ECBM, the model forecast showed total cumulative CH_4 production with the vertical well injector of 41,373.4 t. From the results, application of CO_2 sequestration in a vertical well for ECBM can obtain additional recovery factor of about 1.12 times the primary recovery method (base case). With regard to the pressure depletion, the decrease of reservoir pressure with CO_2-ECBM (magenta line) is not significant as the decrease of reservoir pressure with primary recovery method (green line). It shows that injecting CO_2 into coal seam(s) help in maintaining CBM reservoir pressure. The CO_2 which is injected into coal seam(s) will be adsorbed in the coal matrix. 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. Subsequently, CH_4 is replaced by injected CO_2 and desorbed from coal matrix and it is then flow through the matrix into natural fracture network.

The CO_2 storage mechanism considered in this study is adsorption trapping. In the adsorption trapping mechanism, the accumulation of injected CO_2 is absorbed on the surface of coal matrix. The capacity of this mechanism is mostly depend on Langmuir isotherm (Jasinge and Ranjith 2011). From the simulation results, the model resulted in the CO_2 storage capacity of about 384,579.07 t. With the base case CO_2-ECBM, total of CO_2 injected is 204,814 t while CO_2 that can be stored of about 124,930.5 t. The CO_2 storage efficiency of coal seams was calculated by comparing the CO_2 stored from CO_2-ECBM and the total of storage capacity. From the result obtained, the CO_2 storage efficiency of 32.5%. For the optimization purposes, this number can be increased by optimizing the CO_2 injection operation parameters, e.g. increasing CO_2 injection rate/amount introduced into the coalbed methane reservoir, and using horizontal well as the CO_2 injectivity enhancing technology (Ridha et al. 2017). These are also beneficial to maintain reservoir pressure and increase methane production.

Sensitivity analysis

Having performed CO_2-ECBM technique, a sensitivity analysis was carried out to examine the influences of reservoir permeability on the novel numerical model in

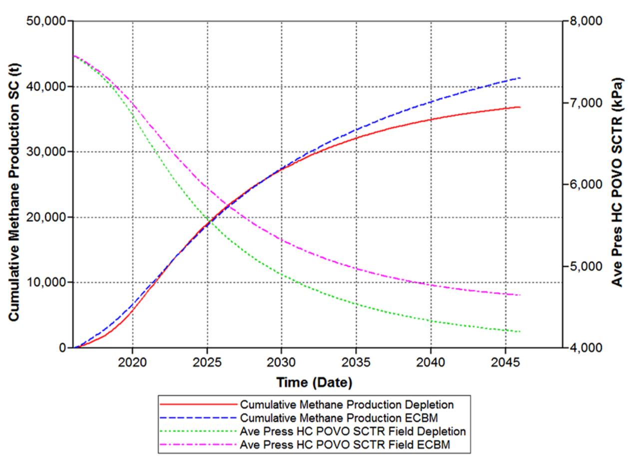

Fig. 2 Comparison of production performance of depletion and CO_2-ECBM recovery

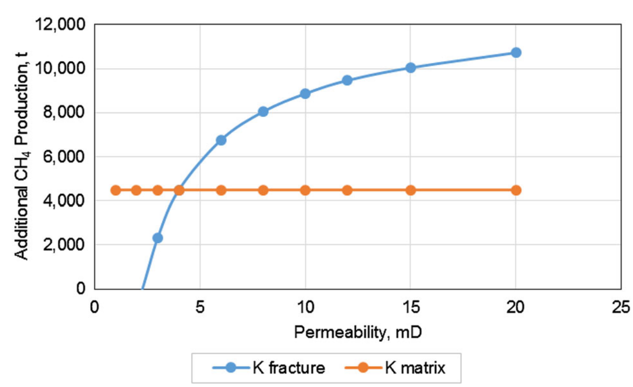

Fig. 3 Permeability versus additional CH_4 production: blue line indicates that CH_4 recovery due to CO_2 sequestration increases proportionally with increments in fracture permeability and vice versa, there is no effect of matrix permeability (*orange line*) on CO_2-ECBM

order to assess the performance of CO_2-ECBM. The recovery factor obtained from the model was examined under the influences of fracture and matrix permeability. Figure 3 shows the influences of reservoir permeability on additional CH_4 production from CO_2-ECBM. From the results, it can be seen that fracture permeability ($k_{fracture}$) has a significant impact on the performance of CO_2-ECBM, and vice versa, there is no effect of matrix permeability (k_{matrix}) on CH_4 production recovery due to CO_2 sequestration. This is caused by gas flow or migration in the coal matrix due to diffusion or differences of the gas molecular concentration (Thimons and Kissell 1973), CH_4 will diffuse from matrix surface to cleats/micro-pores (desorbed from coal matrix), while injected CO_2 is replacing CH_4 and adsorbed in coal matrix. With regard to the fluid flow concept in the porous medium, gas flow in the cleats and natural fractures to the wellbore by Darcy's flow, where the gas rate as a function of fracture permeability. Due to this concept, recovery factor obtained from CO_2-ECBM increases proportionally with an increase in fracture permeability. In regard to CO_2 storage capacity, increase of fracture permeability from 2 to 20 mD leads to increase of CO_2 storage efficiency from 32.1 to 38.2% (Fig. 4). Even though fracture permeability at 1 mD resulted in storage efficiency of 38%, there is no effect of CO_2 sequestration in increasing CH_4 production at this point.

Based on the results of model development and sensitivity studies, the technical criteria of coal seam(s) suitable for CO_2 sequestration with enhanced coalbed methane recovery were then proposed. The key criteria are likely to be:

Homogeneous reservoir: The coal seam(s) reservoir 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 also optimum.

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.

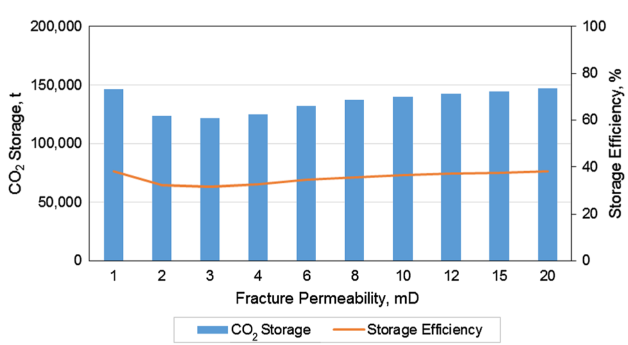

Fig. 4 Fracture permeability sensitivity on CO_2 storage

Fracture permeability: The coal seam reservoir(s) should have fracture permeability more than 2 mD. The injection flow rate through the porous medium is proportional to the fracture permeability. The greater the fracture permeability, the deeper invading CO_2 reaches; it will result in high efficiency of CO_2 sequestration and enhanced coalbed methane recovery.

Suitability of coal seams in South Sumatera Basin for CO_2 sequestration with ECBM recovery

In the South Sumatera Basin, there are two main coal formations; these are the Oligocene Talang Akar and the Miocene Muara Enim formations. Based on a preliminary study by Kurnely et al. (2003), Muara Enim Formation (MEF) is the best coal to be developed in South Sumatera Basin due to the CBM field located in onshore, the infrastructure have been settled, and the markets are in there. Muara Enim coals have potential gas contents of around 7 m^3/t, and CBM targets have low CO_2 which of less than 5% (Stevens and Hadiyanto 2004). Muara Enim coals have also good coal thickness and favourable depth for CBM production (Muksin et al. 2012). With the coal seams are laterally continuous over tens of kilometres (Bowe and Moore 2015), few faults and flat dips (CBMA 2013), and permeability less than 10 mD (Sosrowidjojo 2013), these make coal seams in the South Sumatera Basin in generally, Muara Enim formation in particularly, suitable for the application of CO_2 sequestration with enhanced coalbed methane recovery. With the base case simulation scenario, coal seams in the South Sumatera Basin have good potential for CO_2 sequestration with storage efficiency up to 36.5% (Fig. 4). With regard to the ECBM recovery, the model resulted in additional CH_4 production recovery up to 1.226 times the primary recovery method (Fig. 3). These number can be increased by performing an optimization on the injecting parameters of the CO_2 injection, e.g. CO_2 injection rate and well-spacing optimizations.

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. 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 (S_w matrix = 0 and S_g fracture = 0),

Table 2 Parameter used in sensitivity analysis

Reservoir parameters	Low case	Base case	High case
Prospective area (A), m^2	640,000	1,102,500	1,690,000
Coal seams thickness (h), m	12.5	25	37
Coal density (ρ_b), kg/m^3	1300	1459.27	1500
Gas sorption capacity (GSC), m^3/t	2.5	7	–

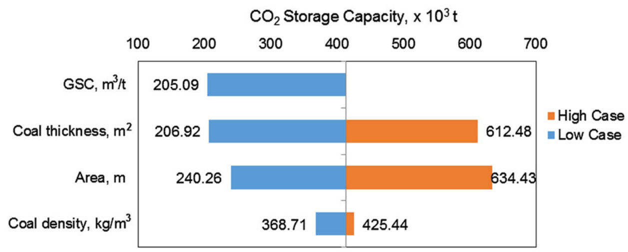

Fig. 5 Tornado plot indicating the influences of different reservoir parameters on CO_2 storage capacity resulted from the simplified OGIP computation (proposed equation)

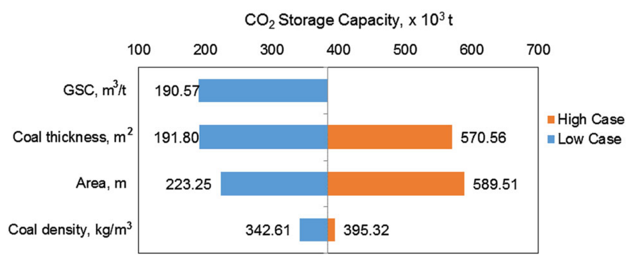

Fig. 6 Tornado plot indicating the influences of different reservoir parameters on CO_2 storage capacity resulted from numerical simulation

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 storage capacity in the coal seams can be calculated as:

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

where $\rho_{CO2} = 1.873$ kg/m^3, $A = 1102{,}500$ m^2, $h = 25$ m, $\rho_b = 1459.27$ kg/m^3, $G_{CS} = 7$ m^3/t, CO_2 storage capacity $= 413.9 \times 10^3$ t. The CO_2 storage capacity resulted from the proposed equation was then compared with the novel 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 summarized in Table 2.

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. Figures 5 and 6 show CO_2 storage capacity resulted from the simplified OGIP computation and numerical simulation. The error obtained for each case was calculated. The average error obtained for 'High' case of 7.53%, 'Low' case of 7.68% and 'Base' case of 7.62%. In average, the total error resulted in about 7.61%. From these results, the error resulted from the simplified OGIP computation or proposed method is not too significant or less than 10%, which is considered good matches and it can be used and applicable to estimate the CO_2 storage capacity in the coal seams. From the results of tornado plot, gas sorption capacity, coal thickness and prospective area prove to be the parameter with large impact on CO_2 storage capacity. It is therefore required that parameter be precisely estimated to improve accuracy of the prediction.

Conclusion

Based on the results of model development and sensitivity studies, the technical criteria of coal seams suitable for CO_2 sequestration with enhanced coalbed methane recovery (CO_2-ECBM) have been fully defined. The proposed key criteria are likely to be homogeneous reservoir, simple structure (minimally faulted and folded), and fracture permeability should be more than 2 mD. Based on these criteria, coal seams located in South Sumatera Basin, especially in Muara Enim formation (MEF), are suitable for the application of this clean coal technology, which can storage CO_2 in the coal seams and help in increasing the CH_4 production recovery. 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. From this study, one can screen the suitable coal seams for CO_2 storage with enhanced coalbed methane recovery purposes and can quickly quantify the CO_2 storage capacity in coal seams without performing numerical simulation.

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