A numerical simulation study of injecting CO\textsubscript{2} into coal bed (enhanced coal bed methane) to reduce GHG emission

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Abstract. Increasing concentrations of greenhouse gases (GHG), including CO\textsubscript{2}, will lead to changes in the Earth’s climate with the consequence of the rise in the global average temperature. Reducing CO\textsubscript{2} atmospheric concentrations by capturing emissions at the source and then storing them in subsurface reservoirs is considered a reliable solution until emission-free energy sources are developed and viable. Depleted oil and gas reservoirs, saline water aquifer, un-mineable coals are common sites for underground storage. The injection of CO\textsubscript{2} in coal beds, known as ECBM is considered one of the most efficient and favorable economic options of all storage because CO\textsubscript{2} is stored and at the same time will improve the recovery of coal bed methane. This method has huge potential as Indonesia hosts many coal deposits, however, exploitation of CBM is still very limited and mostly on pilot project status. The objectives of this study are to realize the potential value of ECBM and understand important operating parameters that will optimize the project. Reservoir simulations are an inexpensive method for predicting optimal trade-offs between these two separated processes (maximum storage/sequestration and maximum CBM production). This study reveals that methane recovery dependent strongly on the injection rate, while coal swelling/shrinkage only affects early production.

1. Introduction

There is a growing concern about anthropogenic greenhouse gas (GHG) emissions because of their contribution to global warming. New technologies are being sought to reduce its emission, and one of the most promising ones is carbon sequestration. This allows the continuation of fossil fuel use before its total dismissal. There are several potential sites and methods for subsurface/underground CO\textsubscript{2} storage include [1]: depleted oil and gas reservoirs in form of enhanced oil recovery (EOR) and enhanced gas recovery (EGR), shallow and deep aquifer, oceans, forests, and coal bed as enhanced coalbed methane production (ECBM).

The main challenge is that cost of capturing CO\textsubscript{2} is high therefore needs to be reduced to improve the economics of the sequestration process. The viable alternative is to combine it with the oil/gas recovery enhancement process thus improving its economics. This method provides the most viable opportunity for near-term yet low net-cost CO\textsubscript{2} sequestration.

Coal deposits are often situated near power generation plants, a big point source of CO\textsubscript{2} emissions, which makes its economics better because of lower pipeline cost and power plant produced flue gas which contains nitrogen. A mix with nitrogen in the injected gas can enhance recovery of the methane recovery even higher. The conceptual synergies of a combination of ECBM and CO\textsubscript{2} sequestration from power plant source are shown in Figure 1 below, where a pretreated CO\textsubscript{2} or flue gas (a mix of CO\textsubscript{2}, N\textsubscript{2}, and hydrocarbon gases) from a stationary power plant is produced and then injected into nearby coal seams. A coal-fired power plant is a large stationary CO\textsubscript{2} point-sources and accounts for 30% of total energy-related CO\textsubscript{2} emissions [2].
Coal deposits in Indonesia are mainly in Sumatra and Kalimantan. The older (Eocene age) coal deposits formed in the Kalimantan CBM appears situated further from markets, however, the plan to move State Capital to Kalimantan could trigger its development. There is another much less prospective coal basin.

Figure 1. The synergy between CO₂ sequestration and methane production [3].

2. World CBM resources
Coalbed methane (CBM) in the US has become an important source of natural gas supply, starting in 1980 now 127 million m³ day (4.5 Bcf/d) – around 10% of total US natural gas production [4]. Total deposits of coal in the US are estimated at 4 trillion tons which can produce nearly 300 trillion cubic feet of natural gas (of pipeline-quality) [2].

In a coal mining operation, where the presence of CH₄ poses a safety hazard, the degasification process reduces this risk as it can replace or supplement mine ventilation. To recover natural gas from both mineable and unmineable coalbeds different types of wells trajectory: vertical, deviated, or horizontal borehole systems have been used. The main problem of the CBM project is generally feasibility due to the low and regulated market price of natural gas. ECBM offers an alternative as the produced methane can be sold to improve the economics of CO₂ sequestration, and surrounding communities/cities get the benefits of cleaner fossil fuel.

Indonesia has the distribution of coal contained in eleven onshore coal basins however only a few of them have been exploited commercially. In the past, it was perceived by CBM operators in Indonesia that the CBM potential wasn’t very great because the coal is low rank and too shallow. After all, open-pit mines that produce lignite or sub-bituminous coal in Indonesia possess insignificant CH₄ control issues [5]. The success of Powder River Basin CBM development in the US, which is also low-rank development might show that it is not all true. Improved understanding of the coal geology in Indonesia that the surface coal mining in Indonesia even though shallow but become gas charged at target depths (100-1,500 m) of CBM over broad areas; and c) strong evidence from nearby petroleum well mud logs penetrating these deep coal seams recording gas kicks that indicates large quantities of methane is adsorbed on the coal seam.

3. CBM geology of Indonesia
Coal deposits in Indonesia are mainly in Sumatra and Kalimantan Island formed during two primary ages (Miocene and Eocene ages). Muara Enim Formation in Sumatra (of younger Miocene age) even though low rank (lignite to sub-bituminous with Ro of 0.3 to 0.5%) however extremely thick and more prospective. The Mangus Seam located in the Southern South Sumatra basin spans over 140 km distance surrounding the Bukit Asam coal mine, while other seams are shorter in distance (50 km). In general, compared to CBM reservoirs in the Powder River basin, Indonesia Miocene coal deposits in Indonesia are deeper (which is good), thicker, and generally have a higher ranking.

The older (Eocene age) coal deposits formed in Kalimantan island for example Tanjung Formation less prospective, due to their thinner (1 – 10 m net) and deeper, however, may be locally perspective. In general, the Kalimantan CBM appears situated further from markets, however, the plan to move State Capital to Kalimantan could trigger its development. There is another much less prospective coal basin.
such as the Jatibarang basin (due to extreme depth), South Sulawesi basin (thin layer), the Bengkulu basin (has complex geological structure) and the Ombilin basin is (small basin and has high CO$_2$ content).

![Map of Indonesia showing CBM potential in Kalimantan and Sumatera](image)

**Figure 2.** CBM potential in Indonesia [5].

It is estimated that Indonesia has approximately 450 Tcf of prospective CBM resources and by assuming typical reserve resource conversion rates of $>10\%$ and adequate investment (reserves are dependent on investment), CBM reserves are in the range of 50 – 130 Tcf, this number represents 1/3 of conventional gas reserves), that can be exploited by a three-fracture-per-well completion strategy [4].

CBM exploitation activities in Indonesia has been pioneered by VICO (Kutai Basin) and MEDCO (South Sumatera basin) since 2005. However, the success was not significant making some CBM contractors had to farm out the area. According to 2017 SKKMIGAS data, currently, the active operation area are around 40 areas in Kalimantan and Sumatera [6]. Low oil prices, Land acquisition permits, environment permits (UKL/UPL), Rig License permit, procurement process, and others have slowed down the progress. However, the Government of Indonesia has made a breakthrough by simplifying the process in the area of Regulatory, Procurement Policy, and Operating Procedure Guideline to increase the Total Reserves and Energy Resilience of Gas in Indonesia. New Operating guidelines including the recommendation of 19 items of current practices in drilling and completion adopted from standard conventional oil well drilling to be changed to simplify the process and reduce the cost.

4. **Coal seams characteristics**
   The coal seams can be characterized by interconnected zones (i) the bulk matrix and (ii) fracture zone (consists of face and butt cleats). Fractures have much larger permeability (the ability of the rock to pass the fluid flow) than the bulk matrix, and therefore most of the flow occurs in the fractures. Solid coal comprises the bulk matrix and its microscopic pores network and hosts almost all of the methane (CH$_4$) in sorbed form. During the production phase, the methane will desorb from the coal matrix and diffuses to the cleat (fracture) network before transported to a production well (see Figure 2) and surface piping network. When CO$_2$ is injected into the coal seam it will diffuse more easily into the bulk matrix (sorbed onto the coal surface) and displacing CH$_4$ in the matrix [7]. CO$_2$ is chemically bound or sorbed to the coal surface in a large volume of highly concentrated CO$_2$. This process will reduce its mobility and decreasing the chances that it will leak/escape into the atmosphere.
CO₂ and N₂ have different mechanisms for sequestration and enhanced production of methane. Complex interactions of the physical and chemical processes occur until the equilibrium state is achieved in the gaseous state (inside the fracture) and sorbed state (in the coal matrix) simultaneously. The coal capacity to adsorb/hold gases is considerably more for CO₂ than either methane (CH₄) or N₂ with an approximate ratio of 4:2:1. A partial-pressure disequilibrium will be formed in the gaseous phase inside the coal fracture system. The desorption/adsorption process of individual components will continuously occur until the equilibrium state is achieved for both the sorbed and gaseous [8].

In the case of N₂ injection, the equilibrium ratio of CH₄ to N₂ in the gaseous state is 1:3 (while in the adsorbed state is 2:1). Therefore, as pure N₂ is injected, it will flush the methane out from the fracture/cleats, reducing the partial pressure of CH₄ in the cleat-system gaseous phase to essentially ‘zero’. And as a result, methane desorbs from the matrix (methane stripping). In the case of CO₂ injection, rather than displacing methane in the cleat system, it becomes quickly and preferentially adsorbed onto the coal. And as result methane is ‘pushed’ out from the matrix into the fracture system.

The efficiency of the ECBM project depends on the reservoir and operating parameters such as: well length, well type, number of wells, the pressure of injection, coal permeability, and coal- CO₂-methane interaction (sorption capacity). During primary production, a phase where (original) reservoir pressure is used to produce methane (without gas injection), will continue until the reservoir pressure is depleted sufficiently low to begin an injection. CO₂ injection then is started until breakthrough (the time when the producer wells start producing gas with a concentration of CO₂ higher than the threshold value). The final grid used for all simulations was an 11 x 11 x 2 grid that represents a 6100 x 6100 feet region. Well, control parameters for simulation were using constant pressure wells instead of constant injection rate.

5. Results and discussion

Generally, the performance of the combination of Enhanced recovery and CO₂ sequestration process is affected by cleat system density, methane sweep efficiency, and gas composition. Factors such as well type (vertical/horizontal), well density (number of wells per area), reservoir pressure in combination with fracture/cleat system properties will affect sweep efficiency. The injected gas composition will also affect the performance as the departure will occur from the chemical equilibrium between the gasses and the coal [3]. To improve understanding of methane production response in changing of the reservoir and operating parameter, the rock model for simulation is constructed with parameters: thickness 18 m, initial pressure 76 bar, cleat porosity 0.001 (fraction), cleat permeability 10 mD and reservoir temperature 45 °C.

The simulation model is created and run using Eclipse 300 Multiphase simulator by constructing a homogeneous model representative of coal seam found in Indonesia (Figure 3). The model consists of a 11x11x2 grid model with permeability 10 mD and porosity 0.1%. The depth of the coal seam is 1,253 m containing originally 100% methane in matrix and cleat (fracture network).

Our work focused on the impact of varying operating parameters and composition of injected gas (CO₂ and N₂) on methane recovery. Operating parameters varied are: (1) number of wells in the pattern, (2) well type, (3) injection rate, and (4) injected gas type. In the first case number of wells are varied within 202 x 202 m size pattern (representing ¼ of the 15-acre pattern), ranging from 1 – 8 producers/1/4 of the full pattern (the reduced model to ¼ pattern is to make simulation runs quicker). It is found that an increasing number of wells will accelerate before converging within 3 years (Figure 4). Well type also being varied between horizontal and vertical wells (for producers and injectors) (Figure 5). It is clearly shown that horizontal wells outperform vertical however for a not very long time before they are the same. Injection rates are sensitized from 6,000 m³/d to 12,000 m³/d and it can be shown that production rates and total recovery are dependent on the injection rate until a critical rate when above it the injected gas will quickly breakthrough to the producer as indicated in the yellow line in Figure 6.
The impact of coal swelling/shrinkage was also tested and the result shows that they do not affect the recovery significantly. Injected gas types are also varied between no gas injection (primary recovery), CO\textsubscript{2} and N\textsubscript{2} (flue gas from power plant often contain a significant amount of N\textsubscript{2}). Figure-7 below shows the potential improvement of an injection of N\textsubscript{2} over CO\textsubscript{2} and no gas injection where Enhanced Coal Bed Methane with CO\textsubscript{2} increase the recovery slightly but N\textsubscript{2} ECBM is superior to CO\textsubscript{2} because of the methane stripping in the cleat process.

**Figure 3.** Simulation rock model.

**Figure 4.** Effect of number of wells/pattern to the total methane recovery.
Figure 5. Effect of well type to the total methane recovery.

Figure 6. Effect of number of wells/pattern to the total methane recovery.
6. Conclusions
The methane recovery is affected by a number of wells, well type, injection rate, and type of gas injected. However, the first three parameters have only accelerated the recovery and within a short period of time (3 years in this study) they converge. Injection gas type behaves differently in this case, where N₂ injection recover higher methane due to the methane stripping process from the cleat network, while CO₂ tends to be adsorbed in the coal matrix. This indicates that flue gas produced from the power plant can be also injected with significant result.

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