Abstract

Uncertainties of CO2 injection-sequestration in a CBM is driven by the complex process of gas desorption-controlled mechanism attributed to the natural characteristics of CBM and to the impact of the wells engaged in the reservoir. This work presents the reservoir characterization and simulation process focused on natural gas production and subsequent CO2 injection into an unmineable coal seam in the Marshall Country West Virginia. Two coal seams (Pittsburgh and Upper Freeport) are the subject of this pilot CO2 sequestration project. Methane is produced from both coal seams; however CO2 is injected only in the Upper Freeport which includes four wells. The shallower Pittsburgh coal is used to observe and detect any possible leakage. The objective is to build a reservoir simulation model that is capable of matching the methane production history and forecast field potential capacity for CO2 injection and sequestration. Although injection has taken place in two reasonably close wells, these wells exhibit different production and injection behavior.

A commercial simulator is used for modeling. Three realizations of the reservoir were built and history matched base on different Langmuir isotherms. The model which leads to a better approximation of the actual injection profile is selected for further analysis. Upper Freeport formation characteristics, its CO2 storage capacity and CO2 distribution in the reservoir are presented in this article. The model can be used to define safety margins for the maximum bottom-hole pressure during injection.

Introduction

Sustain economic growth by providing sufficient energy and controlling the CO2 emissions as byproduct of producing Energy from fossil fuels is one of the most challenging tasks for engineers. The dilemma of burning hydrocarbons to produce energy or to stop producing energy from burning the fossil fuels to avoid environmental harm can be solved by sequestering the CO2 emissions into the ground. CBM formations besides producing CH4, they have the capacity of storing CO2 because of the absorptive properties of coal. The process of injecting CO2 and sequester it not only helps to reduce green house effect it also helps the improvement of gas recovery. The process of estimulatating the CBM by injecting CO2 to produce more CH4 is called enhanced coalbed methane or
ECBM. A CBM is considered an unconventional reservoir. Unlike conventional reservoir where the gas is compressed by the pressure of the formation during millions of years, in CBM the majority of the gas is stored in the internal divisions of the coal, called the matrix. CBM is a reservoir formed by matrix and fractures, the small fractures are called cleats.

The gas flow mechanism in CBM can be summarized in 3 stages. For CH4, it starts first by producing water from the fractures. Secondly when the reservoir pressure is dropped, it reaches the proper pressure allowing the gas to flow from the cleats surfaces to the fractures then to the wellbore. Third, there is a molecular diffusion through the coal matrix in which the gas is displaced to the cleats to eventually reach the wellbore. An inverse but similar process occurs when CO2 is injected. The difference of these two processes is the adsorption time for CO2 which varies from the adsorption time of CH4 and no water is injected. Coal adsorbs CO2 quicker than CH4.

The adsorptive capacity of coal for CO2 prevails over CH4 as it has been proved (1). This adsorptive capacity is measured by the Langmuir Isotherm (2). But the capacity to store CO2 depends also on the characteristics of the CBM reservoir (3). Mainly Porosity and permeability characteristics drive the flow of gas through the coal. The CBM may have unknown reactions regarding the compressibility of the coal when CH4 is produced and when CO2 is injected. By history matching first the CH4 production and later the CO2 injection, will define the values of porosity and permeability allowing the estimation of future CH4 production and amount of CO2 that can be injected.

A pilot project to develop ECBM takes place in Marshall County West Virginia. Over this field there are two CBM formations. Pittsburgh CBM is the shallower formation. The other, Upper Freeport CBM, is found below of the Pittsburgh CBM. In both CBM formations, wells are configured horizontally. Upper Freeport formation is where CO2 is injected.

This study focuses on the behavior of Upper Freeport CBM while CO2 is injected. In this formation CH4 has been produced prior to the injection stage. The complexity of Appalachian CBM is included in the construction of the reservoir simulation model. In the targeted CBM layer the wells are drilled horizontally, but these CBM formations are characterized by having variable thicknesses (4).

Numerical reservoir simulation models provide a better understanding of how the gas flows from the reservoir to the wellbore (5). Heterogenities and complexities can be added to the models to mimic real conditions of the hydrocarbons inside the formations. Numerical reservoir simulation is the main tool to analyse the behavior of CO2 in CBM.

Langmuir Isotherm
The amount of gas contained or adsorbed in the coal at equilibrium conditions can be calculated using the Langmuir isotherm equation. The general Langmuir isotherm equation for gas is the following:

\[ G_c = \frac{V_L P}{P + P_L} \]  

If in this equation, Langmuir Volume \( V_L \) and Langmuir Pressure \( P_L \) are measured along with gas content \( G_c \), then Pressure \( P \) can be calculated as shown in the following equation.

\[ P = \frac{P_L G_c}{V_L - G_c} \]  

The Pressure \( P \) describes the pressure at which gas starts desorbing from the coal. The capacity of producing gas from the CBM reservoir will be directly related with the magnitude of this pressure \( P \). By history matching the CH4
production the capacity of the reservoir will be constrained because porosities and permeabilities in the fracture and matrix will make harder or easier for the gas to flow and be produced. The objective of performing history matching is to characterize the reservoir in order to evaluate and predict the behavior of the CBM reservoir.

**Research Field Description**

There are two CH4 producing CBM formations. The first one is Pittsburgh where two wells have been drilled. The wells, MH3 and MH12 are located in the north and south of the research area respectively. Both wells have been drilled horizontally. According to elevation measurements of wells MH12 and MH3 the Pittsburgh CBM is located above sea level. Wells MH12 and MH3 started production on January 2005 and have produced CH4 (methane) until January 2010. Figure 1 demonstrates the location of Pittsburgh wells. Thickness of Pittsburgh CBM is averaged between 5ft to 6 ft with no major changes.

The other formation, Upper Freeport CBM is located below Pittsburgh CBM, separated by approximately 500 ft. Four wells have been drilled in the Upper Freeport CBM. There are four wells, MH5 located in the north, MH18 and MH20 located in the center and MH11 located in the south. All wells are drilled horizontally. The average thickness of Upper Freeport CBM varies from approximately 5 feet to less than a foot.

![Figure 1 Pittsburgh CBM formation.](image-url)
Methodology

Langmuir Isotherm delineates the CH4 production of the CBM and CO2 injection capacity of the reservoir. For this study, the Langmuir Isotherm is introduced into the reservoir modeling analysis. Referring to equation 2 where pressure depends on values of $V_L$, $P_L$, and initial gas content $G_c$, these values control the CH4 production but it gets constrained when history matching is performed. The Upper Freeport CBM started production on all four wells. After two years of production, wells MH18 and MH20 were shut in while well MH11 was still producing CH4. The production in Well MH5 only lasted for a year. Then CO2 injection started on wells MH18 and MH20 after approximately 2 years of being shut in.

Initial values for Langmuir Isotherm have been provided, well logs were also provided as well. Porosity and permeability are deducted by history matching CH4 production and later CO2 injection. Thickness and depth are deducted from the logs. During the CH4 production phase the CBM was characterized but as CO2 injection took place in the reservoir this characterization was not capable of history matching actual CO2 injection rates. The reservoir simulation model has to history match CH4 production and also the CO2 injection phase. If the reservoir parameters are modified and they get overestimated in order to have a history match for the later injection, then Langmuir Isotherm is slightly changed to generate a change in CH4 production. Properties such as Porosity and permeability in the matrix and fracture are necessarily changed in order to have a history match. This alteration in the porosity and permeability affects the CO2 injection.

The initial constraints for CO2 injection consists of keeping a constant pressure of 700 psi and injects the equivalent of 27 short tons of CO2 during 2 years that is 20,000 short tons of CO2. In order to evaluate different injection scenarios, it is necessary to have more than one numerical reservoir simulation model but characterized differently and at the same time it should keep the history match for CH4 production. Langmuir Isotherm dictates the CH4 production capacity, therefore magnitudes of the CBM reservoir properties have to be modified to achieve the history match with actual CH4 production data. The magnitudes in the CBM properties affect the further CO2 injection, even though the CH4 production has already been history matched. If the CBM is characterized with low porosity and permeability, the expected flow of CO2 injection is less than if such property values were highly

![Figure 2 Upper Freeport CBM formation](image)
During the injection phase the amount of CO2 that each well, MH18 (North) and MH20 (South) receives depends on the pressure that each the well can hold. If one well receives less CO2 than the other one, it means that the well is reaching the maximum allowed pressure and also it means that its characterization in terms of thickness, permeability, porosity or any other parameter is relatively low if it is compared to the other well where the flow of CO2 is more abundant.

In this study three different scenarios are evaluated. As seen in figure 3, the scenarios are based on three Langmuir Isotherms leading to three different numerical reservoir simulation models, the higher the value of P the greater CH4 production. If in the numerical reservoir simulation model the production is overestimated then to history match it with actual production, some parameters, specifically, porosity and permeability are forced to be decreased but if they reach very low values then the CO2 injection gets underestimated because the CO2 can not flow.

Results and discussion

The following table 1 present results of 3 different scenarios proposed based on different characterizations. The red line indicates the cumulative CO2 injection for well MH18 and the blue line indicates the cumulative CO2 injection in well MH20. The differences among the three scenarios are their characterization. Each reservoir simulation model has been previously history matched for its CH4 production before CO2 started; therefore each model has different injection profile during the CO2 injection process. These scenarios were established before actual CO2 started on the research field in Marshall County, West Virginia.
Table 1 Results of CO2 injection rate profiles

<table>
<thead>
<tr>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,600 short tons of CO2</td>
<td>20,713 short tons of CO2</td>
<td>6,677 short tons of CO2</td>
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The following figure 4 shows the actual CO2 injection for wells MH18 and MH20. The flat segments of the graph indicate that CO2 was not injected during the time indicated. Notice how the injection pressure has been gradually increased to reach the boundary of 700 psi.

![Figure 4 Actual Cumulative CO2 injection for wells MH18 and MH20](image)

After comparing actual data with the scenarios proposed, scenario P3 fitted the actual injection of CO2. The following figure 5 shows how the cumulative CO2 injection is history matching the injection in well MH18. The simulated gas injection rate follows closely the actual data for injection especially at the last 10 day period of injection recorded data. The blue circled points indicate the actual injection whereas the continuous line indicates the simulated CO2 injection.
Figure 5 CO2 injection History Match Results Scenario 3 Well MH18, Low permeability

The following figure 6 shows the injection history match approach for Well MH20. As it can be seen the reservoir model does not have enough injectivity to store the CO2 due to its low permeability. This indicates that the pressure in well MH20 is increasing rapidly.

Figure 6 CO2 injection History Match Results Scenario 3 Well MH20, Low permeability

If the actual data fits the scenario 3, then the amount of CO2 injected over two years, 27 short tons of CO2 per day, cannot be completed. I order to overcome with the fact of not injecting the required amount, other scenarios based on different injection pressures are evaluated. As figure 7 shows, 3 different injection pressures are evaluated, 670 psi, 800 psi and 1,000 psi.
The following figure 8 shows the results of CO2 injection predictions based on the 3 different injection pressures. As indicated each reservoir simulation model reaches 20,000 short tons of CO2 at different times but after 2 years none of these scenarios complete the objective of injecting the whole amount of CO2 in 2 years, 20,000 short tons.

By analyzing the results from the figure 8, the injection pressure of 800psi reaches the amount of CO2 first than the models with 670psi and 1000psi as their injection constraints. The 1,000psi injection pressure reservoir simulation model cannot inject the amount asked at an earlier time due to an increase in the well pressure, therefore, the injection rate is managed to be decrease until the well pressure allows it and continue with the injection.
Conclusion

In this study 3 different scenarios for CO₂ injection have been developed based on the characterization obtained on History Match production of CH₄. The 3 scenarios were confronted to actual CO₂ injection data. The results from the third scenario fitted actual CO₂ injection data. This scenario describes a very low permeability that makes difficult for CO₂ to flow through the coal. The capacity of the CBM reservoir to inject CO₂ is driven by the characterization of the reservoir that is defined during the CH₄ production phase.

Measurements on Langmuir Isotherm determine the gas production capacity of the CBM reservoir. The studies of CO₂ injection performance in CBM reservoirs are necessary to make decisions. Numerical reservoir simulation models help to visualize likely scenarios of CO₂ injection. Having at hand the results of different CO₂ injection profiles will help the production engineers to plan and place the proper equipment in the field to adjust likely scenarios.

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References

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Symbols

CH4: Methane  
CO2: Carbon Dioxide  
CBM: Coalbed Methane  
ECBM: Enhanced Coalbed Methane  
V: Volume of gas  
Gc: Gas Content  
VL: Langmuir Volume  
P_L: Langmuir Pressure  
P_c: Langmuir Pressure  
TVD: True Vertical Depth.