Design and Operational Considerations of a Pilot Project for Sequestration of Carbon Dioxide and Enhanced Coalbed Methane Production in an Eastern Coal Seam

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Abstract
Because of increased concern about anthropogenic carbon dioxide emissions, the geological sequestration of carbon dioxide is being examined as one means of reducing these emissions. Unmineable coal seams are considered good candidates for such sequestration projects, because they have served as excellent storage reservoirs for sorbed gases for geological time periods. Additionally, the enhanced methane production from these reservoirs makes a favorable contribution to the economics of the projects.

A pilot project is being implemented in northwest West Virginia to examine the technical feasibility of this form of sequestration. The project consists of an isolated 3000 ft square pattern in a thin coal seam. The pattern is formed by four 3000 ft long horizontal wellbores on the exterior of the square, which serve as production wells. At the center of the pattern are four horizontal wellbores that serve as either producers or injectors. Methane production occurs through all wellbores until the reservoir pressure is reduced to a specified low value, at which time the central wellbores are converted to carbon dioxide injectors while the exterior wellbores continue methane production. Carbon dioxide injection and methane production continues until carbon dioxide concentration reaches ten percent in the production wells. At that time the project is terminated.

The design factors considered were the choice of the lengths and orientation of the central wells, while the operational factors considered were the operating pressures of the injection wells. When the central wellbores are oriented perpendicular to the exterior wellbores the configuration is referred to as the plus-configuration, and when the central wellbores are oriented toward the corners the configuration is called the x-configuration. Most of the studies conducted on this pattern have focused on the plus-configuration. An important conclusion of the previous work was that the diffusion time constant for the coal may be an important parameter to consider when one designs a sequestration project. This paper examines the effect of injector well length on project performance for the x-configuration for the same range of injection pressures, diffusion time constants and reservoir anisotropies that were considered for the plus-configuration. On the basis of the ultimate amount of carbon dioxide sequestered, at low anisotropy ratios central injectors of approximately 1000 ft were found to be optimum at lower injection pressures, but
the length shortened to approximately 850 ft at the highest injection pressures. For larger
anisotropy ratios injector lengths of approximately 1100 ft were optimum at low pressures or for
short diffusion time constants. In contrast to the plus-pattern, the use of injectors shorter than the
optimum length can result in significantly reduced performance, especially for short diffusion
time constants and high anisotropy ratios. For low anisotropy the x-configuration yields better
sequestration performance, but for high anisotropy the plus-configuration with unequal injector
lengths performs very well.

Introduction

Recently, the geological sequestration of carbon dioxide has received considerable attention as a
means of reducing the emissions of anthropogenic CO2. Sequestration in unmineable coal seams
is one option with great potential because CO2 becomes chemically bound or sorbed to the coal
surface, reducing its mobility and decreasing the chances that it will escape back into the
atmosphere. Furthermore, the CO2 may displace additional methane from the coal seam, making
a favorable economic contribution to the sequestration project.

For the purpose of modeling the flow in coal seams, the coal seams can be represented as two
interpenetrating media: a fracture network, composed of the cleats, and the bulk coal matrix. The
fracture network consists of fractures generally oriented in the direction of the principal stress
field (face cleats) and in the orthogonal direction (butt cleats) (Figure 1, Remner et al, 1984 ).
Although the fractures comprise only a very small volume fraction of the coal (1-2% or less),
they contain the largest permeability, and therefore are the major flow path in the reservoir. The
bulk matrix is comprised of the solid coal and its network of microscopic pores and generally has
a higher porosity than the fractures but a much lower permeability. Almost all of the methane
found in the bulk matrix is in sorbed form. During production the methane desorbs from the coal
and diffuses to a cleat (Figure 2, Remner et al, 1984), where it flows to a production well under
the influence of an applied pressure gradient. Similarly, in CO2 sequestration, the injected carbon
dioxide enters the cleat system from which it diffuses into the bulk matrix and becomes sorbed
onto the coal surface. The diffusion process within the coal matrix is characterized by a diffusion
time constant. The length of this diffusion time constant relative to project length has been
shown to have a significant effect on project performance (Sams et al, 2002b).

The success of any sequestration/enhanced coalbed methane project depends on a number of
reservoir properties, which determine the best engineering design. Factors such as lengths and
orientation of wells and injection and production well pressures, combined with reservoir
properties such as the methane-CO2 sorption isotherms and coal permeability, are expected to
have significant effects on the success of a sequestration project. The goal of these projects is to
maximize the amounts of methane produced and CO2 sequestered before the concentration of
CO2 in the produced gas exceeds the limits imposed by economics of separating the CO2 from
the produced gas. In addition it is necessary to maintain production and injection rates above
limits imposed by economics. A state-of-the-art coalbed methane simulator has been used to
study the effects of these operational parameters and reservoir properties on a generic coal seam
sequestration project.
Code Description

PSU_COALCOMP is a coalbed methane reservoir simulator developed within the Petroleum and Natural Gas Engineering program of The Pennsylvania State University. The code is a two-phase, multi-dimensional, dual porosity compositional simulator that treats the multi-component sorption that takes place within the coal matrix. The multi-component sorption model uses the Peng-Robinson equation of state (Peng and Robinson, 1976) to calculate the required thermodynamic functions. Three different models are provided for the sorption isotherms within the code, Langmuir, Toth, and UNILAN. The Langmuir is a two-constant model, while the other two are three-constant models. The gas/water flow within the cleat system is simulated by the standard two-phase Darcy model based on relative permeabilities.

The flow within the coal matrix, as well as the sorption/desorption dynamics, is represented by a lumped-parameter system that characterizes the process with a time constant, \( \tau \). The value of the time constant is closely related to cleat spacing in coal. It characterizes the rate at which gas exchanges between the micropores and the cleat system. The value of the time constant is approximated by the following equations:

\[
\tau = \frac{1}{D_{mi} \times a} \quad (1)
\]

\[
a = \frac{5.7832}{R_{mi}^2} \quad (2)
\]

where \( D_{mi} \) (ft\(^2\)/D) represents the micropore diffusion coefficient and \( a \) represents the shape factor for cylindrical matrix elements. \( R_{mi} \) (ft) is taken as the cleat spacing. For smaller values of \( \tau \), the exchange of material between the micropores and the cleats is rapid, and equilibrium between the micropores and the cleats is more easily maintained during a production and/or injection process. Equilibrium is not maintained when the time constant becomes a sizeable fraction of the characteristic time of the process.

The simulator has a number of options for controlling the wells within a simulation. Wells may be opened to flow, shut in, or converted according to a number of criteria selected by the user. These features facilitate the use of the simulator to study coalbed methane reservoirs undergoing either primary production or enhanced recovery schemes. The details of the mathematical formulations for both the fluid flow model and the multi-component sorption model may be found elsewhere (Manik et al, 2002). The simulator has recently been modified to include both the Palmer-Mansoori (Palmer and Mansoori, 1996) and Sawyer/ARI (Sawyer et al, 1990) models for the variation of coal permeability due to matrix shrinkage and swelling. The present study does not make use of these models; however, a companion paper (Bromhal et al, 2004) does examine these effects.
Project Background
The simulations described in this report are for a generic coal seam sequestration/ enhanced coalbed methane project using horizontal wells as producers and injectors. The simulations model an isolated pattern that consists of four 3000 ft horizontal wells around its perimeter, forming a square with four additional horizontal wells located at the center of the pattern. Horizontal wells are used because they provide high connectivity with the cleat system of the coal seam increasing production and injection performance (Taber and Seright, 1992). When the central wells are oriented orthogonal to the perimeter wells they are said to be in the plus-configuration. When the central wells are oriented diagonally within the pattern they said to be in the x-configuration. To date most studies of this pattern have examined the performance of the plus-configuration. During primary production, methane is produced from all wells until the reservoir pressure is reduced to an appropriate value for injection to begin. In a previous paper (Sams et al, 2002a), it was found that the final results were not very sensitive to this variable, so for all simulations presented here, we used a primary production time of 115 days. At that time the center wells are converted to injectors, and CO₂ injection is begun and continued until the concentration of CO₂ in the produced gas reaches a specified threshold value, which was 10% for this study.

Because of symmetry within the pattern, all runs were performed on a quarter of the pattern. The grid used for all simulations was a 36x36 grid that represents a 6100 ft x 6100 ft region, which was one quarter of the pattern plus an external region of 4600 feet on each side (Figure 3). The procedure for determining the size of the external region was discussed in a previous paper (Sams et al, 2002a). All wells were simulated as constant pressure wells (as opposed to constant injection rate).

Prior studies have separately addressed the sensitivity to coal properties for a fixed operational policy (Odusote et al., 2002) and the sensitivity of project performance to certain operational parameters for a fixed set of reservoir properties (Sams et al, 2002a). The examination of the interaction between coal properties and operational parameters was begun in another study that focused on the interaction between the time constant, τ and the injection well pressures (Sams et al, 2002b). The primary result of that study was that the sequestration performance of a project is negatively effected when τ is a significant fraction of the injection period. The effect of methane content has also been examined (Sams et al, 2003). While the methane content has a strong effect on production performance, the effect on sequestration performance is small. Lower methane content does result in slightly higher sequestration performance. The effects of anisotropy on the plus-pattern were examined (Bromhal et al, 2003 and Smith et al, 2003) and found to be significant. However, the use of unequal length injectors, where the ratio of injector lengths depended on the anisotropy ratio yielded good performance.

The basic parameters for the simulations may be found in Table 1. For the purpose of simulating different permeability anisotropy ratios the larger permeability is fixed at the base value and the smaller permeability is reduced by the proper amount to obtain the desired ratio. Certain scaling properties are expected to hold to a reasonable degree of accuracy allowing these results to be extended to similar but not identical situations. For instance, provided that the coal seam is not
so thick that gravity segregation becomes important, the total amount of carbon dioxide sequestered and the amount of methane produced are proportionally related to the coal thickness although the timing will be altered. Similarly, the time required by the project scales inversely with cleat permeability. Thus, these results may be used to estimate the performance of projects for other values of permeability provided the effects of the diffusion time constant are accounted for. For this reason the variation of these parameters is not important in a study that optimizes the amount of CO₂ sequestered; however, when economic factors are taken into account, they can play a key role.

Discussion of Results

We performed suites of runs for anisotropy ratios of 1:1 (isotropic), 2:1, 4:1, and 8:1. Each suite of runs examined the performance of the project for eight diagonal well lengths from 420 ft to 1400 ft and for seven injection pressures from 385 psia to 685 psia for a range of diffusion time constants from 1.2 days to 57.9 days. The results of these simulations are displayed in figures 4-11. Figures 4a-11a depict production performance, while figures 4b-11b depict sequestration performance. Since the behavior shows a systematic change as the injection pressure is increased from 385 psia to 685 psia, only results for the lowest and highest injection pressure are shown.

The production performance was only weakly affected by the diffusion time constant. The largest effect was at high injection pressure with low anisotropy. Since much of the methane that is produced is from the region external to the pattern, the length of the project is the principal factor in determining production performance. Short injection wells and low injection pressures result in the longest project times and thus produce the most methane. Increasing well length or injection pressure decreases project length and the amount of methane produced. An increased anisotropy ratio results in earlier breakthrough with a resulting reduction in methane produced. This behavior is the same as that observed for the plus-configuration applied to an isolated pattern (Sams et al, 2002b). This behavior contrasts with that observed for a pattern in a fully developed field where only the methane within the pattern is produced. In the latter case the amount of methane produced is controlled by the sweep efficiency and correlates well with the amount of CO₂ sequestered (Smith et al, 2003).

On the basis of the ultimate amount of CO₂ sequestered, at low injection pressures an injector length of 980 ft was optimum or near optimum for the entire range of time constants and anisotropy ratios. Higher anisotropy ratios favored slightly longer injectors. In these cases 1120 ft injectors were marginally better, especially for short time constants. Higher injection pressures shifted the optimum length to slightly shorter values, with 840 ft injectors being optimum at low anisotropy ratios and 980 ft injectors being optimum or near optimum for high anisotropy values. For the plus-configuration the maximum in performance was quite broad for the isotropic case, with little loss in performance for injectors significantly shorter than the optimum length (Sams et al, 2002b). The peak in CO₂ sequestered vs. well length sharpened significantly with increasing anisotropy (Bromhal et al, 2003 and Smith et al, 2003). In the x-configuration, the use of injectors shorter than the optimum length can result in significantly reduced performance even in the isotropic case. The loss in performance is especially large for short diffusion time constants and high anisotropy ratios.
The sequestration performance of the x-configuration can be significantly better than the plus-configuration for the isotropic case. For short time constants, the optimal performance for the x-configuration is about 15% better than that of the plus-configuration at low pressures and rises to about 20% at high pressures. For long time constants the performance of the x-configuration is about 10% better over the entire pressure range. The sequestration performance of the x-configuration shows a stronger dependence on the time constant than the plus configuration, especially at higher pressures and for the longest injectors. For higher anisotropy ratios, the plus-configuration with unequal injector lengths can provide sequestration performance as good as or better than the x-configuration.

**Conclusions**

The use of the x-configuration can result in better sequestration performance when there is low anisotropy. However, this advantage is lost for higher anisotropy ratios where the plus-configuration with unequal length injectors can produce superior performance. Injectors of approximately 1000 ft produce optimum or near optimum performance for the x-configuration over a wide range of injection pressures, anisotropy ratios, and diffusion time constants. The use of injectors that are significantly shorter than the optimum length can result in a large loss in project performance, as measured by the amount of CO₂ sequestered.

<table>
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<th>Property</th>
<th>Value</th>
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<td>Rock Density</td>
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<tr>
<td>Sorption Pressure constant (CH₄, CO₂)</td>
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<tr>
<td>Sorption Saturation Pressure</td>
<td>800 psia (saturated condition)</td>
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<td>Coalface Pressure at Producers</td>
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References


Figure 1. Plan view of coal seam showing cleat structure and matrix blocks. (Remner et al, 1984)

Figure 2. Schematic of methane flow dynamics in coal seams (Remner et al, 1984). CH₄ desorbs from the solid coal, diffuses through the bulk matrix, and flows into and through the cleats. The pathway for CO₂ sorption is exactly reversed.
Figure 3. Gridding used for all simulations. The quarter of the in-pattern area (upper left, in gray) has a much finer grid than the external pattern.
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**Figure 4.** Methane produced and carbon dioxide retained for an anisotropy ratio of 1:1 and an injection pressure of 385 psia.
Figure 5. Methane produced and carbon dioxide retained for an anisotropy ratio of 1:1 and an injection pressure of 685 psia.
Figure 6. Methane produced and carbon dioxide retained for an anisotropy ratio of 2:1 and an injection pressure of 385 psia.
Figure 7. Methane produced and carbon dioxide retained for an anisotropy ratio of 2:1 and an injection pressure of 685 psia.
Figure 8. Methane produced and carbon dioxide retained for an anisotropy ratio of 4:1 and an injection pressure of 385 psia.
Figure 9. Methane produced and carbon dioxide retained for an anisotropy ratio of 4:1 and an injection pressure of 685 psia.
Figure 10. Methane produced and carbon dioxide retained for an anisotropy ratio of 8:1 and an injection pressure of 385 psia.
Production Performance for an Anisotropy Ratio of 8:1 and an Injection Pressure of 685 psia

![Production Performance Graph](image)

(a)

Sequestration Performance for an Anisotropy Ratio of 8:1 and an Injection Pressure of 685 psia

![Sequestration Performance Graph](image)

(b)

Figure 11. Methane produced and carbon dioxide retained for an anisotropy ratio of 8:1 and an injection pressure of 685 psia.