MODELING CO_2 SEQUESTRATION IN ABANDONED MINES

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Abstract

Coal is a known adsorbent of Carbon Dioxide (CO_2) as well as nitrogen and hydrocarbon gases. Methane is a product generated during the coalification process, which is then adsorbed within the micro porous structure of the coal. Along with methane, nitrogen and carbon dioxide (CO_2) are also commonly found in coalbed gas, which is generally referred to as coalbed methane, or CBM. This is especially true in coal mine gas, where atmospheric gases penetrate the coal during mining, but methane is generally the dominant species.

CO_2 is preferentially adsorbed on coal, relative to methane and nitrogen. Therefore, if CO_2 is injected into an abandoned coal mine, the CO_2 will displace adsorbed methane. Injection and subsequent adsorption of CO_2 onto the carbon contained in the coal remaining within and peripheral to an abandoned coal mine will trap the CO_2, effectively sequestering it from the atmosphere and thereby reduce the amount of this greenhouse gas (GHG) in the atmosphere. Both methane and carbon dioxide are GHG's, the effectiveness of carbon emission mitigation or sequestration is measured in metric tonnes of CO_2 equivalent (CO_2e).

An abandoned mine complex near an active coal-fired power plant has been selected to investigate the effectiveness of this concept. The authors have modeled this mine complex using a numerical flow simulator that accounts for the adsorption of multiple gas species on the coal. This model is used to predict the volume of CO_2 sequestered, given a variety of injected gas compositions (CO_2 and nitrogen) that are based on processing the flue gas from the power plant. Physical determinants for the effectiveness of this process are the adsorptive capacity of the coal for the gases, the permeability of the coal, the amount of coal exposed to the CO_2, and the pressure at which the mine can hold the gas. The economic feasibility of the envisioned project is determined by the unit cost of the CO_2 sequestered versus the value of the greenhouse gas (GHG) reduction credits that could be generated.

Introduction

Methane is a by-product generated during the coalification process. It is then adsorbed within the micro porous structure of the coal, and can be released by reducing the partial pressure of methane in the coal fracture system. The recovery and utilization of methane from both active and abandoned coal mines has increased dramatically in recent years, with several large projects operating in both North America and Europe. Use of coal mine methane (CMM) that would otherwise escape to the atmosphere also has the advantage of reducing the emission of a highly potent greenhouse gas, as methane is 21 times more potent than carbon dioxide (CO_2) and could qualify for carbon emission reduction credits in the emerging GHG market.

Abandoned coal mines could also be used as a carbon sink because CO_2 has an affinity for adsorbing to coal, that is greater than methane, and will effectively displace the methane molecules from the adsorption sites within the micro pore structure of the coal. A study to verify and quantify this was performed as a first step in determining the economic feasibility of sequestering CO_2 in abandoned underground coal mines. The advantages of injection into an abandoned coal mine versus an unmined coal bed are identified below:

- The large exposed surface area in the mine workings will facilitate the adsorption of the CO_2;
- The mining process enhances fracturing of the coal and therefore the permeability to the flow of gas into the unmined perimeter as well as into the coal remaining as pillars;
- The water saturation of the coal near the mine workings will be low because the mining activity has lowered the pressure and drained the water, facilitating movement of gas into the coal; and
- The injection pressure will be low, so the cost of compression will be low.

The mine complex chosen for study consists of three relatively small abandoned underground coal mines located near a small active coal-fired power generation facility. This could provide a steady source of flue gas, should the study indicate that the project appears feasible and a pilot project be implemented.

The following parameters are significant in determining the CO_2 storage capacity of a mine:

- The size of the mine workings;
- The thickness of the coal;
- The permeability of the coal;
- The pressure at which the mine can be operated as a storage vessel;
- The pressure at which methane is contained in the coal;
- The adsorption isotherm of the coal for CO_2, methane, and nitrogen, and; and
- The distance to which the CO_2 will penetrate beyond the outer walls of the mine.

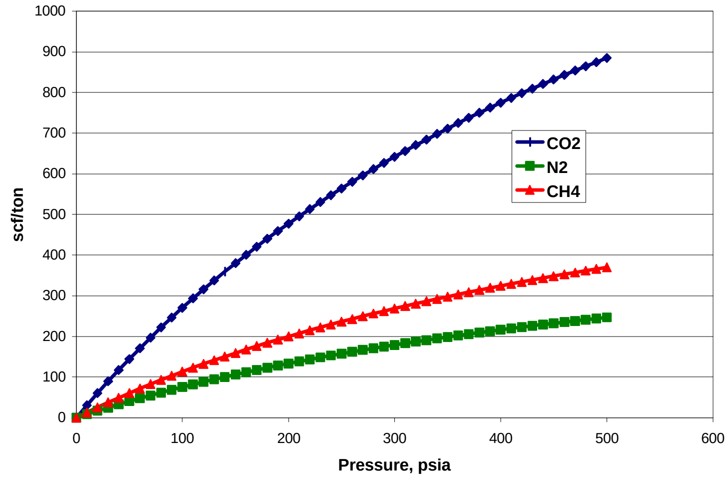
At the selected mine, which covers approximately 350 acres only one seam had been mined, with a total of about 90,000,000 cubic feet of coal having been extracted. This is not typical, as many mines cover thousands of acres, exploiting numerous seams with cumulative production of several billion cubic feet of coal. The targeted seam of the subject mine is a 7.5 foot thick coal seam. The coal thickness influences not only the volume of coal available for CO_2 sequestration, but the surface area across which the gas can enter the coal. The permeability of the coal to the flow of gas, together with the surface area are primary factors determining the rate at which the gas can move into the coal.

The study used an injection pressure of 100 psia, but the actual capacity of a mine to hold pressure will have to be determined on a case-by-case basis. The mining process reduces the pressure of the coal remaining in the mine, as well as the coal within the periphery of the mine; therefore, the methane content per ton of coal will be relatively low. This will, however, facilitate the flow of flue gas into the coal. The distance of penetration over time will be determined by the permeability of the coal, but could also be enhanced by placing wells in strategic locations as material sinks to extract methane before the CO_2 reaches the well. The feasibility of this process will be the subject of a future study.

Modeling Methodology

A computational fluid dynamics simulator from The Computer Modeling Group, Inc. was used to model the injection and adsorption process through time. This finite difference simulator can model multiple component adsorption using the extended Langmuir formulation and accounts for diffusion from the adsorbed state in the coal micro pores to cleat system using a dual porosity formulation. The numerical model consists of a single coal layer, with 30 cells in the I (north/south) direction and 30 cells in the J (east/west) direction. The adsorption isotherms used in the simulation are shown in Figure 1.

Figure 1: Adsorption Isotherms Used in CO2 Sequestration Simulation

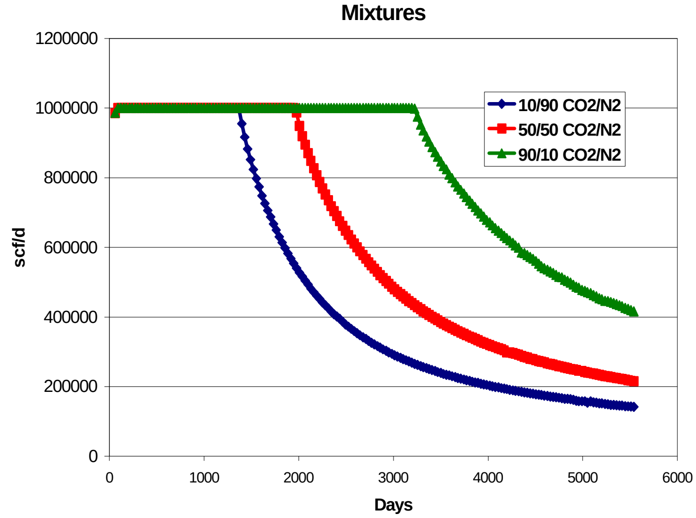


The cells that fell within the mined out areas of the model where assigned a porosity of 50% because approximately 50% of the coal has been removed by the room and pillar mining method that was employed in the mine. These cells were also assigned a high permeability of 40,000 millidarcies. The cells peripheral to the mine were assigned porosity value of 5% and a permeability of 20 millidaries. The pressure in the mine and surrounding coal was initialized at 25 psia.

Results

Flue gas of three different compositions of CO_2/nitrogen (10/90, 50/50 and 90/10) was injected into the Easterly most section of the mine over a simulation time of 18 years, with an initial injection rate of 1,000 Mcf/d. Once the maximum injection pressure of 100 psia was reached, the rate decreases as the capacity of the coal to adsorb more gas decreases. The injection rate through time for the three compositions is shown in Figure 2. The maximum pressure is reached and the injection rate declines most rapidly for the flue gas composed of 90% nitrogen and 10% CO_2, which is close to a typical composition of flue gas emitted from power plants. However, the injected gas mixture with 90% CO_2 and 10% nitrogen, has an initial decline that occurs several years later and declines at a lower rate. The efficiency of adsorption of the component gases determines the overall efficiency of adsorption of the gas stream. Poorly adsorbing nitrogen more rapidly fills the

Figure 2: Injection Rate Behavior of the Three CO2/N2 Mixtures



pore space and increases the pressure, contrasting with the behavior of CO_2, which rapidly adsorbs onto the coal and thereby lowers the pore pressure. This allows more gas to fill the pore until the capacity of the coal to adsorb gas at that pressure is reached. Therefore, when the mixture contains a high CO_2 content, a greater amount of CO_2 will be adsorbed before the maximum injection pressure for the abandoned mine is reached.

Options and Issues for Commercial Development

Table 1 shows the mass of CO_2 and nitrogen adsorbed and stored in the coal as a result of 18 years of injection. For a CO_2 sequestration project to be realized, the capital and operating costs of processing a flue gas stream (stripping off the nitrogen) and injecting the CO_2 need to be low enough that sales of the GHG reduction credits will return a profit. The current GHG market is speculative and the value of GHG credits is uncertain. Values of GHG reduction credits have been cited recently to range from $0.50 to $10.0 per metric tonne of CO_2 equivalent.

Table 1: Metric Tons of Components Sequestered

Component	Composition (CO_2/N_2)		
	10/90	50/50	90/10
CO_2 (CO_2e)	13,879	90,164	220,638
N_2	131,475	94,787	29,467
Total Injected	145,354	184,951	250,105

$CO_2$and nitrogen are known to enhance the production of methane in conventional coalbed methane (CBM) fields by two mechanisms; reducing the partial pressure of the system and physical displacement. Nitrogen enhances the production of methane by reducing the partial pressure of methane in the fracture system of the coal (the cleat system) which accelerates desorption of methane while maintaining the flow potential of the system. CO_2 is preferentially adsorbed over methane therefore it not only reduces the partial pressure in the cleat system, but competes for adsorption sites on the coal, displacing the methane molecule.

One possible way to enhance the value of CO_2 sequestration is to use the flue gas injection to recover methane from the abandoned mine and surrounding coal. This could be done by placing wells around the periphery of the mine. This will provide pressure sinks to draw displaced methane from the coal and draw the injected flue gas farther into the surrounding coal. Eventually the nitrogen and CO_2 will breakthrough to the wells diluting the methane. At this point, the well could be abandoned as a production well, and a replacement drilled farther away from the mine. The abandoned well could then be converted to an injection well, allowing for more direct access to coal that has not yet reached its adsorptive capacity for CO_2. This process of stepping out, could, in theory, be implemented on numerous occasions; again depending on the adsorptive capacity of the coal for the gases, the permeability of the coal, and the pressure at which the flue gas can be injected.

There are significant uncertainties in the data and assumptions that were used to generate these predictions. The largest of which are the permeability, water saturation and pore pressure of the coal surrounding the abandoned mine, and the permeability and water saturation (extent of flooding) of the abandoned mine workings. These can only be resolved by a carefully planned data collection and analysis stage followed by a pilot program that will involve drilling wells and injecting gas. Due to the obvious advantage of injecting high CO_2 concentration mixtures, a project such as the one described, will need to be combined with a CO_2 enrichment plant, built to cost-efficiently process the flue gas stream.