Enhanced Coalbed Methane – Micro-Pilot Test
At South Qinshui, Shanxi, China

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Abstract

This paper describes the results of a single well micro-pilot test performed at an existing well in the anthracitic coals of the South Qinshui basin, Shanxi Province, China. A set of reservoir parameters was obtained from the micro-pilot test. The field data was successfully history matched using a tuned reservoir model which accounted for changes in permeability due to swelling and pressure change. Prediction of initial performance showed significant production enhancement of coalbed methane while simultaneously storing the CO₂. The calibrated reservoir model was used to design a multi-well pilot at the site to validate the performance prediction. The design is now completed. The recommendation is to proceed to the next stage of multi-well pilot testing and to demonstrate the enhanced coalbed methane (ECBM) technology.

Keywords: CO₂, coalbed methane, ECBM, production enhancement, storage, field test

Introduction

The Alberta Research Council Inc. (ARC) of Edmonton, Alberta, Canada and its associated consortium members including Sproule International Ltd., Computer Modelling Group Ltd. (CMG), SNC Lavalin Inc., Computalog, CalFrac Well Services Ltd. and Porteous Engineering have been actively involved in developing the technology of injecting carbon dioxide (CO₂) or flue gas (mixed N₂/CO₂) into deep unminable coal beds. This technology is called enhanced coalbed methane recovery or ECBM. The benefits of ECBM are twofold: (1) enhancement of coalbed methane (CBM) recovery and production rates and (2) reducing greenhouse gas emissions to the atmosphere and storing CO₂ permanently in coal beds. The Canadian Consortium led by ARC has been working with the China United Coalbed Methane Corp. (CUCBM) of Beijing, China on a project of development of China’s coalbed methane/CO₂ storage technologies. This project is one of the projects selected by the Canadian International Development Agency (CIDA) to be funded under the Canadian Climate Change Development Fund (CCCDF). The goal of CCCDF is to contribute to Canada’s international objectives on climate change by promoting activities in developing countries that seek to address the causes and effects of climate change, while at the same time contributing to sustainable development and poverty reduction. One of the objectives of the project was to perform up to three micro-pilot tests at three different coalbed methane reservoirs in China.

The micro-pilot approach to coalbed reservoir evaluation has three primary goals. The first goal is to accurately measure data while injecting into and producing from a single well. The second goal is to evaluate the measured data to obtain estimates of reservoir properties and sorption behavior. The third goal is to use calibrated simulation models to predict the behavior of a larger scale pilot project or full field development.
Measured data include the injection rates, surface and bottom-hole pressure and temperature while injecting CO₂, the surface and bottom-hole pressure and temperature during shut-in periods, and the bottom-hole pressure and temperature, gas and water production rates, and gas composition during producing periods. The micro-pilot was designed in six stages as follows:

Stage 1. Inspection of wellhead equipment.
Stage 2. Isolation of the #3 coal seam from the lower #15 coal seam and installing additional downhole and surface equipment.
Stage 3. Initial production testing to determine baseline reservoir properties.
Stage 4. Intermittent injection of CO₂ for up to 30 days followed by a 30-day shut-in period.
Stage 5. Production testing after the CO₂ injection period.
Stage 6. The final shut-in test.

The six micro-pilot stages have been successfully completed in a single well of a 9 well field in the southern part of the Qinshui basin, Shanxi Province, China (Figure 1).

The Field Test

The test well is the structurally highest well of all nine wells in the field and is the original well drilled and production tested before any of the other wells were drilled. Based upon the field production data, this well had commingled production of approximately 1 million m³ of gas and 35,000 m³ of water from two coal seams (#3 and #15 of the Carboniferous Permian Shanxi Formation) starting in March 1998. However, the well was shut-in for a substantial amount of time from April 1999 to December 2000. The gas to water ratio steadily increased after the well was put back on production, producing 30 to 40 m³ of water per day. It was determined that most of the water is coming from a water-wet sand just above the lower coal seam. The lower water sand was isolated prior to initiating the micro-pilot by setting a bridge plug just below the #3 coal seam. The purpose is to allow easier interpretation of results. The completed #3 coal seam has a net thickness of 6 meters and lies at a depth of approximately 500 meters.

Before the injection of CO₂, the well was put on production for 134 days starting on October 28, 2003 and a set of baseline data were collected. Injection of CO₂ started on April 6, 2004. Zhongyuan Oil Field supplied the liquid CO₂ and its transport. It also furnished personnel to perform the injection using a pump skid designed and commissioned by the ARC. The liquid CO₂ was injected at an injection pressure, which was less than the fracturing pressure of approximately 8 MPa (1,150 psig). 192 metric tonnes of CO₂ were successfully injected into the #3 coal seam through 13 injection cycles, each cycle based on injecting one truck load of CO₂. Each injection cycle was a daily cycle of injection and soak. A slug of 13 to 16 metric tonnes of CO₂ was injected each day. The evaluation of the shut-in / fall-off data during the soak period between injection cycles was performed using the ARC/Tesseract well test software, which can evaluate well test data, where the permeability is varying as a function of the changing reservoir pressure and the adsorbed gas content [1, 2]. CO₂ injection was completed on April 18. The well was shut-in for an extended soak period of about 40 days to allow the CO₂ to come to equilibrium with the coal.

The well was placed on production from June 22, 2004 for 30 days. This portion of the micro-pilot was the most important as the production rates and gas composition data were required to estimate the sorption behavior and to calibrate a reservoir simulator to predict the behavior of full-scale pilots and full-field development. A number of operational problems were experienced during this stage, and these were successfully resolved. For example, sections of the tubing burst and were replaced; the pump was plugged and was pulled and cleaned; and the wireline gauges failed and were replaced with self-contained gauges.
A final shut-in test was carried out to obtain estimates of reservoir properties and near-well conditions. The well was shut-in on August 2, 2004. The self-contained pressure gauges were retrieved on August 18, 2004.

**Micro-Pilot Test Results**

The field operation of the first micro-pilot test in China was successfully completed [3]. The average reservoir pressure of the #3 coal seam was 1,241 kPa (180 psia) at a depth of 472 meters (m). The absolute permeability of the coal seam prior to CO₂ injection was 12.6 milli-darcy (md), which was based on an effective permeability to gas of 1.8 md and a gas saturation of 40.8 percent. A total of 192 metric tonnes (103,611 Sm3) of CO₂ were injected into the formation. A preliminary analysis shows that the injectivity to CO₂ decreased initially but was stabilized during the injection of the 13 slugs of CO₂. The composition of the gas on initial flow back after CO₂ injection was 70% CO₂ and 30% methane (CH₄). After one month of production, the CO₂ has dropped to 45% and the methane has risen to 55%.

The set of estimated reservoir parameters from the micro-pilot test was used in history matching using a reservoir model incorporating the ARC Permeability Theory. Based on this analysis, CMG’s GEM® numerical simulator has been calibrated based on the history match of the micro-pilot test results (Figures 2 and 3). Prediction of initial performance shows significant production enhancement of CBM while simultaneously storing the CO₂. The next stage was to design a multi-well pilot at the site to validate the performance predictions and demonstrate the ECBM technology.

**Multi-Well Pilot Design**

The proposed multi-well pilot design is an inverted 5-spot pattern, although a three well line drive has also been considered. The original test well used for the single-well micro-pilot test will be one of the corner producers (PW-1). Three existing wells in the vicinity of PW-1 will be the other corner producers (PW-2, PW-3 and PW-4). A new CO₂ injector well (IW), will be drilled approximately at the center of the pattern (Figure 4). All wells will be completed in the #3 coal seam only, similar to the single-well micro-pilot test.

In the design of the multi-well field pilot, a region of approximately 150 acres (780 m × 780 m) is considered which contains the five pilot wells. The reservoir model was first validated based on history match of the historic primary CBM production from the four existing producing wells. Then, numerical prediction of the multi-well field pilot performance was performed based on the following operating conditions:

- Continue CBM production at all four wells at their respective bottom-hole pressures
- Continue history matching of all four wells
- Start CO₂ injection at a constant rate of 22,653 m³/d (or 0.8 MMscf/d)
- Inject CO₂ to #3 coal seam only

It is found that significant enhancement in the CBM production was predicted after CO₂ injection at all four wells. Enhancement factors ranging from 2.8 to 15 were seen from the four wells (see Table 1). Enhancement factor is defined as the ratio of the average CBM production rate of the CO₂-ECBM case to the primary CBM case. CO₂ breakthrough (i.e., defined as 10% CO₂ by volume in the production gas stream) occurred first at PW-3 approximately 2.7 years after CO₂ injection (closest to the IW) and last (5.1 years) at PW-4 (farthest away from the IW). However, methane production rate increase should be observed at all four wells after 6 months of CO₂ injection (see Figure 5).
### Table 1. 5-Spot Field Pilot Test – Performance Prediction

<table>
<thead>
<tr>
<th>Well</th>
<th>PW-3</th>
<th>PW-4</th>
<th>PW-2</th>
<th>PW-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Breakthrough Time* (year after CO₂ injection)</td>
<td>2.68</td>
<td>5.12</td>
<td>3.83</td>
<td>3.12</td>
</tr>
<tr>
<td>Average CH₄ Production Rate Before CO₂ Breakthrough (m³/day)</td>
<td>ECBM</td>
<td>5,275</td>
<td>3,600</td>
<td>4,657</td>
</tr>
<tr>
<td></td>
<td>Primary</td>
<td>1,883</td>
<td>240</td>
<td>718</td>
</tr>
<tr>
<td>Peak CH₄ Production Rate Before CO₂ Breakthrough (m³/day)</td>
<td>ECBM</td>
<td>6,319</td>
<td>4,901</td>
<td>5,355</td>
</tr>
<tr>
<td></td>
<td>Primary</td>
<td>2,036</td>
<td>627</td>
<td>1,305</td>
</tr>
<tr>
<td>Enhancement Factor**</td>
<td>2.80</td>
<td>15.00</td>
<td>6.49</td>
<td>3.44</td>
</tr>
</tbody>
</table>

* Time after CO₂ injection when 10% CO₂ occurred in production gas stream.
** Ratio of average CH₄ production rate: (CO₂-ECBM)/(Primary CBM).

Due to certain design uncertainties such as pressure and water saturation of the coal natural fracture system at the start of the multi-well field pilot test, a sensitive study of these initial conditions on the pilot test performance was conducted. The initial pore fracture pressure ranging from 1.29 – 3.15 MPa and water saturation ranging from 0.6 – 0.98 were investigated.

Based on the results from the sensitive study, the following multi-well field pilot design was recommended:

- Conduct a five-well field pilot test with one new CO₂ injector and four existing CBM producers in an inverted 5-spot pattern configuration
- Block off water zone and the #15 coal seam (i.e., below the #3 coal seam) with perforation at the #3 coal seam only for all four existing producer wells
  - Perforate new injector well at the #3 coal seam only
- Inject CO₂ at a constant rate of 22,653 m³/d (or 0.8 MMscf/d) for 6 months
  - Injection pressure should be below the estimated coalbed fracture pressure of approximately 8.3 MPa
  - CO₂ breakthrough should not occur at any of the producer wells in the 6 month period
  - The first peak rate of CBM production would be observed at PW-3; however, this would not occur until about a year after CO₂ injection
- During the field pilot test, well bottom-hole pressures, gas injection/production quantities and gas injection/production composition should be monitored at all the pilot wells
- Numerical prediction should be refined from the pre-test prediction as more information such as initial conditions of the near-well regions are available
- Post-test history match of the multi-well field pilot test data will further validate the capability of the numerical model to predict the CO₂/flue gas injection process into coal

### Conclusion

The first single well micro-pilot test at south Qinshui basin, Shanxi Province, China was successful. The field data was successfully history matched using a tuned reservoir model. Prediction of initial performance indicates that significant enhancement of CBM production while simultaneously storing the CO₂ is feasible with the high rank anthracite coal in Qinshui basin (see Figures 6 and 7). A multi-well pilot was designed. The recommendation is to proceed to the next stage of multi-well pilot testing.
Reference


Figure 1. Location of Micro-Pilot Test.  
Figure 2. History Match of Bottom-hole Pressures in Stages 4-6 of Micro-Pilot Test.  
Figure 3. History Match of Gas Composition
Figure 4. Pattern Configuration of the Multi-Well Pilot.

Figure 5. 5-Spot Pilot Test Prediction - Methane Production Rate.

Figure 6. 5-Spot Field Pilot Test Prediction - Cumulative CBM Production.

Figure 7. 5-Spot Field Pilot Test Prediction - CO₂ Inventory.