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Nitrogen enhanced drainage of CO_2 rich coal seams for mining

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A B S T R A C T

Coal seams with high CO_2 gas contents can be difficult to drain gas for outburst management. Coal has a high affinity for CO_2 with adsorption capacities typically twice that of CH_4. This paper presents an analysis of nitrogen injection into coal to enhance drainage of high CO_2 gas contents. Core flooding experiments were conducted where nitrogen was injected into coal core samples from two Australian coal mining basins with initial CO_2 gas contents and pressures that could be encountered during underground mining. Nitrogen effectively displaced the CO_2 with mass balance analysis finding there was only approximately 6%–7% of the original CO_2 gas content residual at the end of the core flood. Using a modified version of the SIMED II reservoir simulator, the core flooding experiments were history matched to determine the nitrogen and methane sorption times. It was found that a triple porosity model (a simple extension of the Warren and Root dual porosity model) was required to accurately describe the core flood observations. The estimated model properties were then used in reservoir simulation studies comparing enhanced drainage with conventional drainage with underground in seam boreholes. For the cases considered, underground in seam boreholes were found to provide shorter drainage lead times than enhanced drainage to meet a safe gas content for outburst management.

1. Introduction

Enhanced coal bed methane (ECBM) involves the injection of a gas to displace the methane within the coal. Initially the injected gas displaces the original coal seam gas from the coal's cleat system, creating a diffusion gradient between gas in the coal matrix and that in the cleat system. With continued injection, the cleat system concentrations of coal seam gas can be very low, meaning that recovery of matrix gas can be more complete than that possible with pressure drawdown through conventional production.

Originally proposed to increase methane recovery for gas production, it has also been considered as a low or zero emissions strategy where CO_2 is injected and stored while displacing the coal bed methane [1]. The interest in this approach has led to several CO_2 ECBM field trials being conducted [2–6]. A challenge with CO_2 ECBM is that coal swells with gas adsorption with the magnitude of the swelling directly proportional to the volume adsorbed [7]. This swelling, within the reservoir, can have a direct impact on the coal permeability, potentially leading to significant decreases in permeability and the ability to inject CO_2 [8].

Nitrogen is a low adsorbing gas for coal and can be readily sourced for enhanced recovery. A large scale field trial of nitrogen injection to enhance methane recovery was conducted by BP in the San Juan Basin starting in 1998. Known as the Tiffany project, a significant increase in methane production of over 5*x* from pre-injection production rates was observed. In addition, permeability was estimated to have increased by an order of magnitude [9].

Nitrogen injection has also been trialled for enhancing methane pre-drainage for coal mine gas management at a northern Bowen Basin coal mine in Australia [10]. Over a period of 4 months a total of 1.6 million m^3 of nitrogen was injected into a 2.6 km long horizontal well while production continued in adjacent horizontal wells that were approximately 150 m to either side of the injection well. It was estimated that the injection enhanced methane production by 383,282 or 4.2 m^3 nitrogen per cubic meter of enhanced recovery. The nitrogen was sourced from a membrane separation plant and required no additional pressure to inject as the outlet pressure from the separator was 900 kPa on a gauge basis. After losses in the gas reticulation system this resulted in an injection pressure of 650 kPa gauge which was adequate for the shallow seams approximately 160 m deep that had already had undergone some gas drainage.

While the composition of coal seam gas is typically predominantly methane, areas naturally high in CO_2 composition and gas content can be encountered during coal mining [11]. Coal tends to have approximately twice the adsorption capacity for CO_2 compared with CH_4 [12]. This means that at relatively low pressures

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there can still be large volumes of gas adsorbed. Because of this, CO_2 areas can pose challenges to gas drainage for outburst management.

Enhanced drainage of CO_2 areas using nitrogen has the potential of improved drainage rates and shortened lead times before mining. This paper presents an investigation of the potential of nitrogen enhanced drainage for CO_2 rich coals. The first part of the paper presents results from laboratory core flooding experiments and history matching of these observations. This experimental work extends that of Connell et al. which presented core flooding experiments where nitrogen and flue gas was used to displace methane from coal and Sander et al. where CO_2 displaced methane [13]. The second part of the paper uses the model properties determined from the history matching in reservoir simulation case studies to evaluate the potential practical benefits for coal mining.

2. Core flooding experiments

2.1. Experimental methodology

The core flooding experiments used intact coal core samples in a triaxial cell arrangement with pressures and gas volumes controlled using high pressure ISCO syringe pumps. Full details of the experimental methodology can be found in Connell et al. [14].

Initially the core sample is put under vacuum to remove any residual gas. In the next step CO_2 is allowed to adsorb into the coal core by maintaining a constant pore pressure until adsorption has equilibrated. N_2 is then injected into the CO_2 saturated sample under constant downstream pore pressure conditions and outflow allowed to occur.

The core floods were performed on two core samples originating from different coal basins. One sample came from the Bowen Basin, Queensland, Australia, the other one from the Hunter Valley, New South Wales, Australia. For the Bowen Basin core sample the same experiment was repeated at a pore pressure of 4 MPa and a confining pressure of 6 MPa (Terzhagi effective stress of 1 MPa). For the Hunter Valley core sample two core floods are performed at a pore pressure of 5 MPa and a confining pressure of 6 MPa. The first Hunter core flood injected pure N_2 to displace the CO_2 from the coal. For the second core flood, a gas mixture, intended to reflect a flue gas from combustion (90% N_2, 10% CO_2), was injected into the CO_2 saturated sample. In summary, the following core floods were performed:

- Bowen basin core sample at 35 °C
  - 4 MPa N_2 displacing CO_2
  - 4 MPa N_2 displacing CO_2
- Hunter Valley core sample at 36 °C
  - 5 MPa N_2 displacing CO_2
  - 5 MPa flue gas (90% N_2, 10% CO_2) displacing CO_2.

2.2. Coal core sample characterisation

The properties of the core samples were determined prior to the core flooding experiments in a separate tri-axial rig following the procedure described in Pan et al. and are summarised Sander et al. [13]. The Langmuir sorption isotherms that were measured in the laboratory for the same coals are presented in Figs. 1 and 2. However, there were discrepancies between the isotherm measured in this work and the gas contents measured during the core flooding experiments. The N_2 isotherm for the Bowen Basin coal core was corrected to match the core flood N_2 gas contents. The measured N_2 isotherm is best described by a Langmuir volume of 21 m^3/t and a Langmuir pressure of 5544 kPa while the corrected

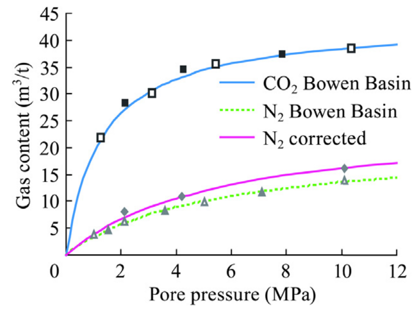

Fig. 1. Adsorption measurements and the best fit Langmuir isotherms for CH_4 and CO_2 for the Bowen basin coal core and the gas contents determined from the volumes of gas adsorbed during the core flood experiments.

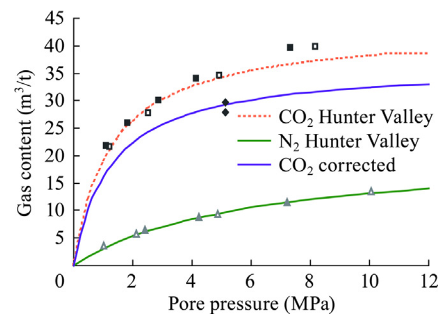

Fig. 2. Adsorption measurements and the best fit Langmuir isotherms for CH_4 and CO_2 for the Hunter Valley coal core including the gas contents measured during the core flood experiments.

isotherm uses an increased Langmuir volume of 25.2 m^3/t to better represent the core flooding data.

As noted in Fig. 1, the unfilled symbols are measurements taken when the pressure was increased; and the filled symbols represent measurements when the pressure was continuously decreased.

As shown in Fig. 2, the unfilled symbols are measurements taken when the pressure was increased; the filled symbols represent measurements when the pressure was continuously decreased.

Similarly, for the Hunter Valley coal core the CO_2 isotherm had to be corrected to improve the agreement with the gas contents measured during the core flooding experiments. The CO_2 isotherm measured was described by a Langmuir volume of 42.84 m^3/t and a Langmuir pressure of 1252 kPa. The corrected CO_2 isotherm uses a reduced Langmuir volume of 36.41 m^3/t with the same Langmuir pressure.

3. Simulation model

The core floods were history matched with a modified version of SIMED II [15]. SIMED II is a dual-porosity, multi-component, compositional reservoir simulation programme specifically designed to describe the behaviour of gas flow in coal seam methane reservoirs.

Following the approach of Connell et al. and Sander et al., the hydrostatic permeability model presented by Connell et al. was used in the history matching [13]. The model differentiates between bulk and pore strain due to gas desorption and is written as:

$$k = k_o e^{-3[C_{pc}(p_c - p_p) + (\gamma - 1)\varepsilon_b^s]} \quad (1)$$

where k is the permeability; k_0 the permeability at reference pore and confining pressure; C_{pc} the compressibility; p_c the change in