EFFECTS OF MATRIX SWELLING ON COAL PERMEABILITY FOR ENHANCE COALBED METHANE (ECBM) AND CO_2 SEQUESTRATION ASSESSMENT PART I: LABORATORY EXPERIMENT

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ABSTRACT

It has been reported that coal matrix swelling/shrinkage associated with CO_2, adsorption/desorption are typically two to five times larger than that found for methane, yet there has been no direct measurements of this effect on permeability of coals to CO_2. The feasibility of ECBM/CO_2 sequestration technology depends very much on the magnitude of matrix swelling effect on permeability, especially in deep, low permeability coal seam reservoirs. The main objective of this research is to investigate the effects of coal matrix swelling induced by CO_2 adsorption on the permeability of different coals which have been undergoing methane desorption under simulated reservoir conditions in the laboratory. Coal and reservoir properties which may impact upon this behaviour will be identified through extensive laboratory testing. This paper – first of two – presents the procedure for the laboratory tests as well as the findings. In the second part, a field permeability model for enhanced methane recovery and CO_2 sequestration, incorporating the findings of the current laboratory tests, would be developed.

Key words: coal matrix swelling/shrinkage, enhanced coalbed methane recovery (ECBM), CO_2 sequestration

I. INTRODUCTION

Laboratory tests on coal samples have demonstrated that methane adsorbed on coal can be completely recovered by cyclic injection of CO_2 [Fulton et al., 1980; Reznik et al., 1984] into large cores under simulated reservoir conditions. In May 1995 Burlington Resources started the world's first CO_2 injection pilot project at the Allison Unit in the Sun Juan Basin [ARI, 1998; Reeves, 2002]. This field pilot has demonstrated that CO_2 injection has the potential to enhance coalbed methane recovery (ECBM) with an added advantage from environmental standpoint that the injected CO_2 can be sequestered permanently in coal.

It is widely accepted that adsorption/ desorption of gas results in the swelling/ shrinkage of the coal matrix. As permeability is directly proportional to the cube of cleat width, a small increase/decrease in cleat width may significantly increase/reduce permeability. Seidle and Huitt [1995] have reported that swelling/shrinkage of coal matrix associated with CO_2 adsorption/desorption are typically two to five times larger than that seen for methane. Therefore, the expected reduction in field coal permeability caused by matrix swelling due to CO_2 pressurisation could be more significant than the increase in permeability already experienced due to matrix shrinkage during primary methane production [Palmer and Mansoori, 1996].

Experimental rigs for multi sample matrix-swelling measurements and single sample simultaneous swelling and permeability measurements under reservoir gas sorption conditions were designed and constructed. Data obtained from long-term CO_2 induced matrix swelling/permeability experiments on different coals was analysed together with the results of multiple CO_2 permeability measurements carried out under simulated reservoir stress and pressure condi

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tions on same coals. Coal and reservoir properties affecting matrix swelling and permeability were identified. The laboratory experiments have demonstrated that matrix swelling has a severe impact on the cleat permeability of coal, with reduction of over one order of magnitude during CO_2 pressurisation.

The main objective of this research was to investigate the effects of coal matrix swelling induced by CO_2 adsorption on the permeability of different coals which have been undergoing methane desorption under simulated reservoir conditions in the laboratory. It was also aimed at identifying coal and reservoir properties affecting matrix swelling and permeability.

II. MATRIX SWELLING/SHRINKAGE CHARACTERISTICS OF COAL UNDER SIMULATED RESERVOIR SORPTION CONDITIONS

Large coal blocks representative of coal ranks from High Volatile Bituminous to Semi-anthracite were collected from opencast or underground coalmines in Europe. These were characterised for rank, cleat system and mechanical/elastic properties for use in the analysis of laboratory matrix swelling and permeability results [Durucan et al., 2003].

A 10MPa high pressure membrane extractor cell manufactured by Soilmoisture Equipment Corp. was used and modified to connect to a strain monitoring bridge consisting of ten independent channels (Figure 1). In view of the length of time (up to three months) required to complete a full cycle of adsorption/desorption tests for solid coal samples, the vessel was designed to take up to five samples simultaneously, with two strain gauges attached to each sample, aligned in the direction of the face and butt cleats. Cubic samples were cut from coal blocks to lengths ranging from 30 to 40 mm. It was ensured that the faces were smooth and in line with the bedding planes. Cleated samples were avoided. 10 mm one-way strain gauges were used during the experiments.

The vessel was first pressurised with helium, in stages up to 7 MPa to evaluate the base mechanical response of the matrix to a non-adsorptive gas. At each pore pressure, the strain readings were allowed to stabilise before moving on to the next pressure step. Once the maximum pressure had been reached, the cell was depressurised in stages. Strains were monitored as before by allowing the samples to attain equilibrium before progressing to the next pressure level. The process was then repeated using 99.7% purity methane gas, followed by pure carbon dioxide. In the case of methane, the sample cell was pressurised to 8 MPa, while for carbon dioxide a maximum pressure of only 5.5 MPa, which was the bottle pressure, was applied. Each time a new gas was introduced, the vessel had to be flushed with a non- adsorbing gas and evacuated in order to eliminate any remnants of the previous gas that may have become adsorbed onto the samples. Examples of matrix strain - pore pressure test results are presented in Figures 2 and 3.

III. COAL PERMEABILITY UNDER SIMULATED RESERVOIR AND GAS SORPTION CONDITIONS

Both the matrix shrinkage/swelling tests described above and the simultaneous swelling and permeability tests presented in the next section involved long-

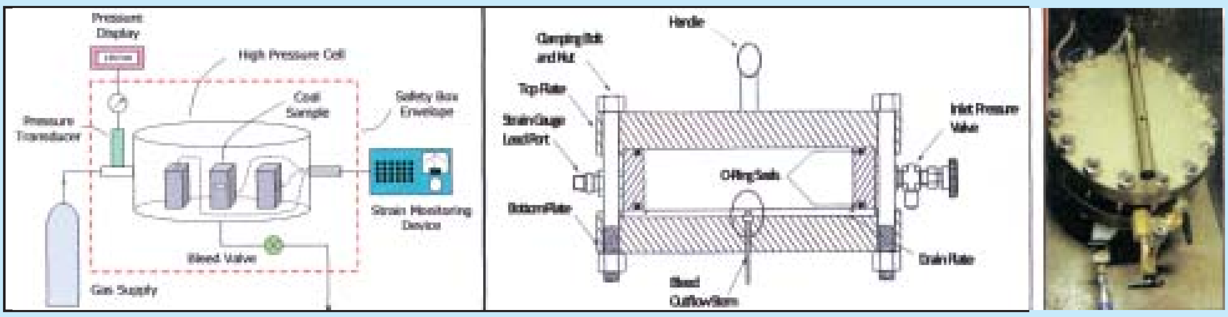

Figure 1
Experimental set-up for matrix deformation tests

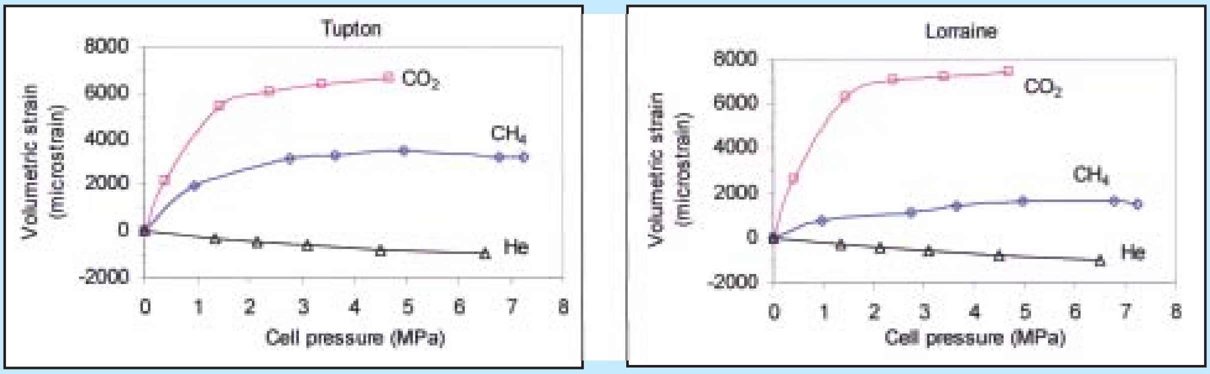

Figure 2
Measured volumetric Matrix Strains for CH_4 and C O_2 for two different rank coals tested

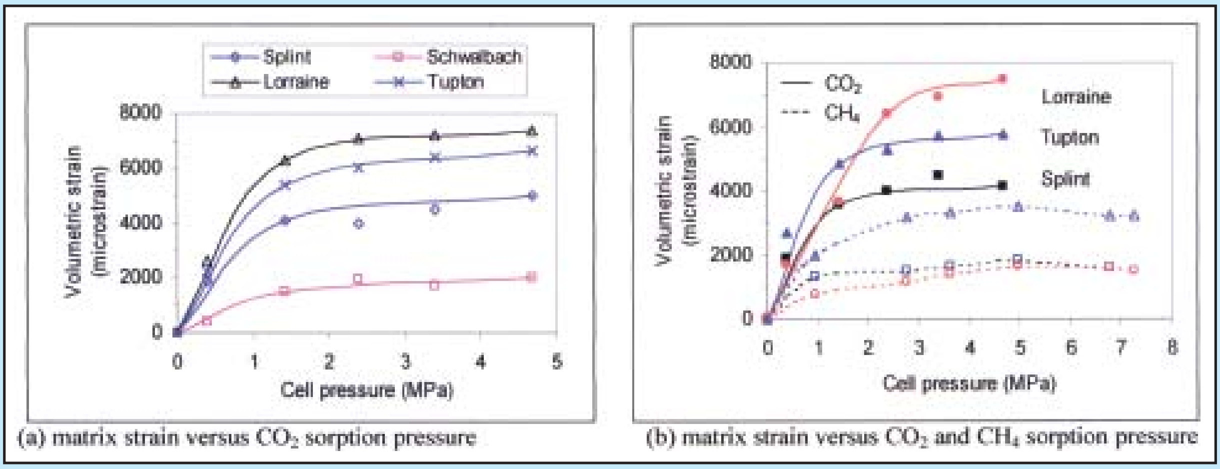

Figure 3
Typical CO_2 and CH_4 matrix strain curves for four different coals, demonstrating a strong correlation between the matrix swelling behaviour and coal rank

term sorption-desorption stages on coal blocks, which normally took three months to complete. In order to obtain a more comprehensive set of permeability data for the coals used, samples from the same coals were subjected to CO_2 permeability experiments under simulated reservoir stress and pressure conditions in the laboratory (up to 12 MPa confinement). CO_2 permeability of intact coals at the same level of confinement used in the simultaneous swelling and permeability tests (7MPa effective stress) varied by an order of magnitude, between 0.1 to 0.01 mD, higher rank coals demonstrating relatively higher permeabilities and a greater degree of swelling. The stress-strain data from these tests were also used to determine the elastic properties of the same coals for correlation and model development purposes. Table 1 summarises the coal properties determined.

IV. SIMULTANEOUS MEASUREMENTS OF COAL MATRIX SWELLING AND PERMEABILITY UNDER CO_2 INJECTION

50 mm diameter cores were used in these experiments. The freshly cut cores were initially placed in a desiccator to help remove any residual gas from the samples. These were then vacuum dried at 60

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^{o}C, in order to avoid oxidation. The same procedure was applied to cube and stress-permeability test samples used above.

In order to achieve a simultaneous measurement of coal matrix swelling and permeability under CO_2 injection, a single core holder Hassler cell was modified by the use of a newly designed and machined platen. The new platen is placed at the upstream end of the cell and allows at least four strain leads to be fed through to gauges attached to one end of the coal sample tested. Figure 4 illustrates the modified platen and associated parts of the Hassler core holder. Normally, two single strain gauges were placed perpendicular to each other on a non-cleated area of the upstream coalface. Two-way rosette gauges were employed where the surface area available was judged to be limited.

After loading the sample, a confining pressure of 7 MPa was applied to the sample. The strain and permeability measurements were carried out in steps with increasing CO_2 sorption pressure. Once the system had fully equilibrated at a given sorption pressure, gas flow was initiated and steady-state flow rate measured by regulating the upstream and downstream pressures. Examples of simultaneous matrix swelling-permeability test results are presented in Figure 5.

V. RESULTS AND DATA ANALYSIS

The experimental work has shown that CO_2 adsorption strains were consistently higher (2 to 4 times depending on rank and matrix elastic properties) than those for methane for all the coal samples tested (Figure 2). These results were in agreement with the measurements reported by Seidle and Huitt [1995]. In addition to sorption-induced swelling, the coal sample also experiences mechanical deformation under hydrostatic gas pressure loading. In an experi-

Table 1
Coal characterisation data obtained during the laboratory experiments and data analysis

	Schwalbach Seam (Ensdorf Colliery)	Splint Seam (Watson Head OCC)	Tupton Seam (Carrington Farm OCC)	Lorraine Basin
Volatile Matter (d.a.f) %	43.6	40.2	35.3	16.5
Fixed Carbon Content (d.a.f.) %	56.4	59.8	64.7	83. 5
Coal Rank	High Vol. Bituminous B	High Vol. Bituminous B	High Vol. Bituminous A	Semi-anthracite
Young's Modulus, E (GPa)	3.2 – 3.9	1.8 – 2.3	1.1 – 1.4	2.2 – 3.0
Poisson's Ratio, n	0.26	0.34	0.36	0.38
c_p x 10^{-6} (MPa^{-1})	21.75	27.55	47.85	226.2
V_L (m^3/kg)	0.006 - 0.010	0.01 – 0.014	0.01 – 0.014	0.016 – 0.02
a (kg/ m^3)	0.40 - 0.66	0.53 – 0.74	0.55 – 0.77	0.53 – 0.66
P_L (MPa)	0.85	0.95	1.05	1.51

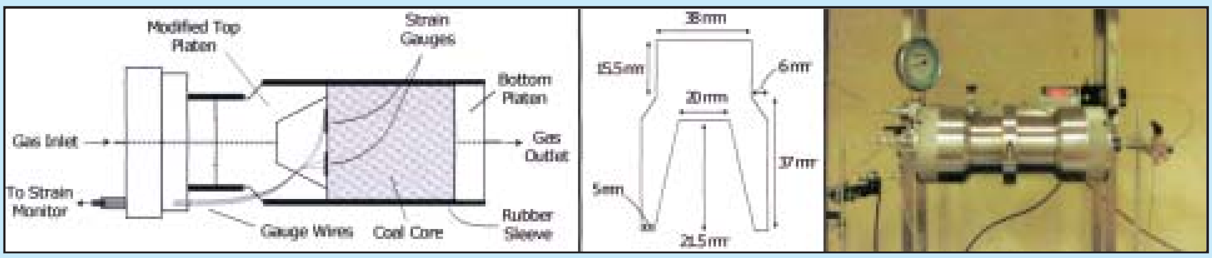

Figure 4
The new platen design and the simultaneous matrix swelling-permeability test cell

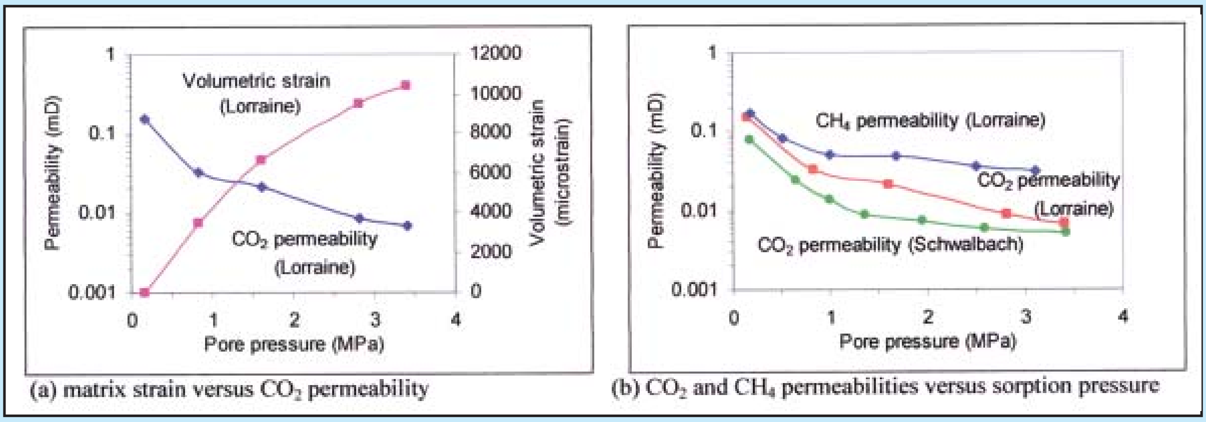

Figure 5
Simultaneous measurements of matrix swelling and permeability on coal samples at a constant confining pressure of 7 MPa

ment to measure matrix swelling of coal due to gas sorption, these two strains counteract. The mechanical compliance coefficient for the coals tested was found from the helium strain data obtained during the experiments. It was observed that there is a correlation between CO_2 matrix swelling and coal rank, with the degree of swelling increasing with rank of coal, as illustrated in Figure 3a.

Simultaneous swelling and permeability tests have shown that matrix swelling has a severe impact on coal permeability, as is illustrated in Figure 5a. As the CO_2 sorption pressure was increased from near zero to 3.5 MPa under a constant confining pressure of 7 MPa, permeability reduction of one order of magnitude was observed for the coals tested. Figure 5b compares CO_2 permeability variation with sorption pressure for two coals (Schwalbach and Lorraine), which have the lowest and highest rank respectively. Both coals show steady decline in permeability with increasing sorption pressure. It is noticeable that the Schwalbach coal permeability follows a gentler trend than the Lorraine coal from 1 MPa onwards. This maybe attributed to the fact that it has a relatively larger matrix Young's Modulus (Table 1) and therefore has undergone less swelling at comparable pore pressures. For comparison, the measured CH_4 permeability for the Lorraine coal is also plotted in Figure 5b. This further underlines the impact of CO_2 matrix swelling on coal permeability.

The above laboratory tests have demonstrated that matrix swelling has a considerable impact on the cleat permeability of coal, with reduction of over one order of magnitude during CO_2 pressurisation. The implication of this observation is that CO_2 injection in field operations could severely impair well injectivity. There is field evidence which suggests that the well injectivity has indeed declined at the early stages of CO_2 injection and then rebounded at the Allison pilot in the San Juan Basin [Reeves, 2002].

The first part of this research was primarily focused upon laboratory assessment of matrix swelling and its impact on coal permeability. In the second part, a field permeability model for enhanced methane recovery and CO_2 sequestration, incorporating the findings of the current laboratory tests, would be developed.

VI. CONCLUSIONS

An investigation into the effects of matrix swelling induced by CO_2 adsorption on the permeability of different coals which have been undergoing methane desorption under simulated reservoir conditions was conducted the laboratory. The laboratory experiments have demonstrated that matrix swelling has a severe impact on the cleat permeability of coal, with reduction of over one order of magnitude during CO_2 pressurisation. The implication of this observation is that CO_2 injection in field operations could severely impair well injectivity. The experimental work has also shown that CO_2 adsorption strains were consistently higher (2 to 4 times depending on rank

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and matrix elastic properties) than those for methane for all the coal samples tested.

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