EFFECTS OF MATRIX SWELLING ON COAL PERMEABILITY FOR ENHANCE COALBED METHANE (ECBM) AND CO_2 SEQUESTRATION ASSESSMENT

PART II: MODEL FORMULATION AND FIELD APPLICATION

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ABSTRACTS

In part II of this two-part paper series, a field permeability model for enhanced methane recovery and CO_2 *sequestration, incorporating the findings of the current laboratory tests presented in part I is presented. 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 and develop numerical models based on the 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.*

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

I. INTRODUCTION

Coalbeds are heterogeneous and are usually characterised by two distict porosity systems – micropores and macropores. The macropores are know as the cleat that can be subdivided into the face cleat, which is continuous throughout the reservoir, and the butt cleat, which is discontinuous and terminates at intersections with the face cleat.

Permeability of coal is regarded as the most important parameter controlling coalbed methane production rate. Due to its dual-porosity structure, where the permeability is predominantly provided by the cleat network which make up the secondary porosity system, the permeability of coal is highly stress-dependent. The face and butt cleats in coal seams are usually sub-vertically oriented. Thus changes in the cleat permeability can be considered to be primarily controlled by the prevailing effective horizontal stresses that act across the cleats.

Coal matrix has been shown to shrink on desorption of gas and to expand again on readsorption. During primary methane production, two distict phenomena are known to be associated with reservoir pressure depletion, with opposing effects on coal permeability [Gray, 1978]. The first is an increase in the effective horizontal stress under uniaxial strain conditions in the reservoir. The second is gas desorption from the coal matrix, resulting in coal matrix shrinkage and thus a reduction in the horizontal stress.

Recent studies [Harpalani et al., 1995 & Seidle et al., 1995] indicate that matrix shrinkage/swelling is proportional to the volume of gas desorbed/adsorbed rather than the change in sorption, as reported by earlier researchers. Given that non-linear Langmuir equations are widely used to describe gas sorption on coal, this implies that the effective stress, and thus the cleat permeability of coal, does not vary monotonously with declining reservoir pressure during drawdown. There is field evidence that suggests a strong rebound in cleat permeability during the process of primary recovery [Palmer and Mansoori, 1996].

Permeability models for primary recovery that use Langmuir-type shrinkage term have been proposed by Palmer and Mansoori [1996] and more recently by Shi et. al. [2002 & 2003]. The two models share the same compression term, but the latter has a stronger matrix shrinkage term, generally resulting in a stronger rebound in permeability in the process of coalbed reservoir depletion.

During enhanced recovery/CO_2 sequestration in coal, adsorption of CO_2 gas, which has a greater sorption capacity than methane, may cause matrix swelling and thus, in contrast to gas desorption, could potentially have a detrimental impact on cleat permeability of coal. Field evidence suggests that the well injectivity has really declined at the early stages of CO_2 injection and then rebounded at the Allison pilot in the San Juan Basin [Reeves, 2002].

The main objective of this research was to develop numerical models for a field permeability model for enhanced methane recovery and CO_2 sequestration, based on the findings of the current laboratory tests presented in part I [Syahrial, 2008].

II. LABORATORY EXPERIMENT

It has been reported by laboratory tests that coal matrix swelling/shrinkage associated with CO2, adsorption/desorption are typically two to five times larger than that found for methane. In part I of this two-part paper series, the effects of coal matrix swelling induced by CO2 adsorption on the permeability of different coals which have been undergoing methane desorption under simulated reservoir conditions was investigated in the laboratory.

Large coal blocks representative of coal ranks from High Volatile Bituminous to Semi-anthracite were collected from opencast or underground coalmines in Europe were used in the laboratory tests. 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]. Figures 1 and 2 show the results of the laboratory experiments.

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

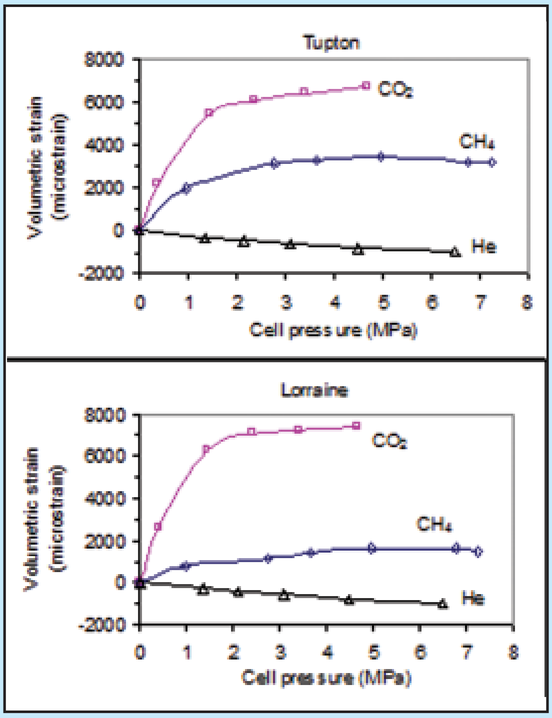


Figure 1
Measured volumetric matrix strains for CH_4 and CO_2 for two different rank coals tested

Examples of simultaneous matrix swelling-permeability test results are presented in Figure 3.

III. MODEL FORMULATION

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 1). These results were in agreement with the measurements reported by Seidle and Huitt [1995]. Assuming that matrix swelling is proportional to the volume of gas sorbed, and the sorbed gas is related to pressure by Langmiur's equation, the relationship between swelling and pressure can be written as [Siedle and Huitt , 1995]:

$$\varepsilon_m = \alpha V_L \frac{p}{P_L + p} \tag{1}$$

where ε_m is strain due to matrix swelling (set to zero at the atmospheric pressure), α is the matrix swelling coefficient (kg/m^3), p is pressure in MPa, P_L and V_L are the Langmuir parameters. In addition to sorption-induced swelling, the coal sample also experiences mechanical deformation under hydrostatic gas pressure loading. The associated strain (again set to zero at the atmospheric pressure) can be related to pressure by:

$$\varepsilon_p = -c_p p \tag{2}$$

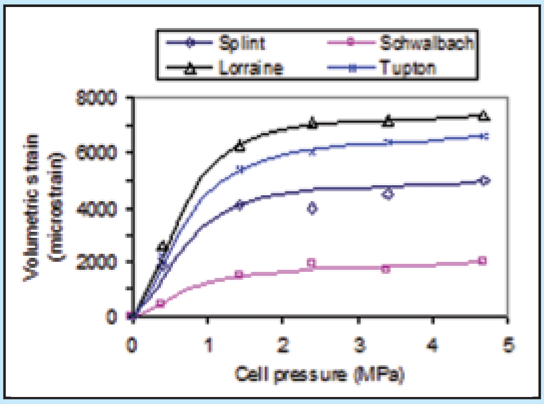
where c_p is the mechanical compliance coefficient of the sample (MPa^{-1}). In an experiment to measure matrix swelling of coal due to gas sorption, these two strains counteract. The strain recorded during the experiment is the net strain, and is given by:

$$\varepsilon_{\exp} = \varepsilon_m - c_p p$$

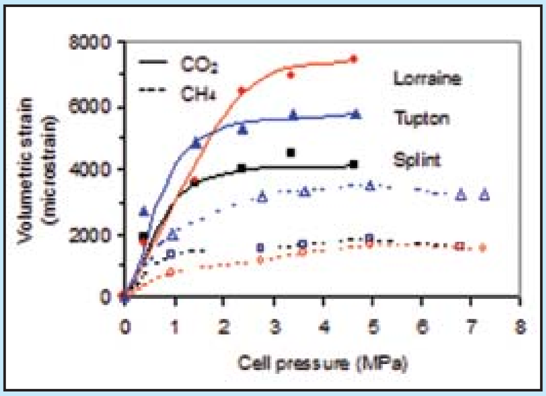
or

$$\varepsilon_m = \varepsilon_{\exp} + c_p p = \alpha V_L \frac{p}{P_L + p} \tag{3}$$

The mechanical compliance coefficient for the coals tested was found from the helium strain data obtained during the experiments. The swelling data shown in Figure 2(a) were fitted to Equation (3) to yield α for each coal. 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 2a.

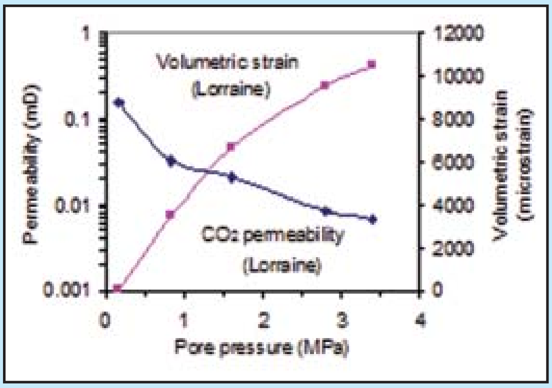


(a) matrix strain versus CO_2 sorption pressure

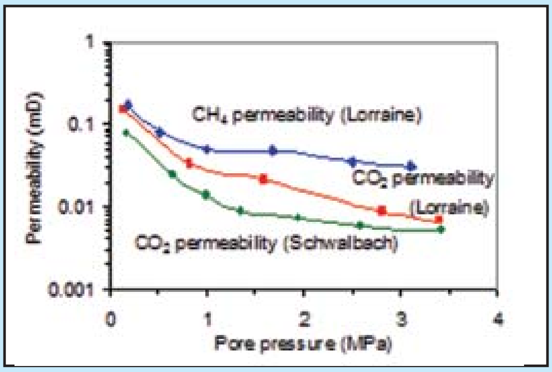


(b) matrix strain versus CO_2 and CH_4 sorption pressure

Figure 2
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



(a) matrix strain versus CO_2 permeability



(b) CO_2 and CH_4 permeabilities versus sorption pressure

Figure 3
Simultaneous measurements of matrix swelling and permeability on coal samples at a constant confining pressure of 7 MPa

Simultaneous swelling and permeability tests have shown that matrix swelling has a severe impact on coal permeability, as is illustrated in Figure 3a. 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 3b 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 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 3b. This further underlines the impact of CO_2 matrix swelling on coal permeability.

VI. FIELD PERMEABILITY MODEL AND APPLICATION

The 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, was developed. During primary methane recovery, drawdown induced changes in the absolute permeability of coal can be described by [Shi *et al*, 2002]:

$$k = k_0 e^{-3c_f(\sigma-\sigma_0)} \tag{4}$$

and

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E\alpha}{3(1-\nu)}[V(p) - V_0] \tag{5}$$

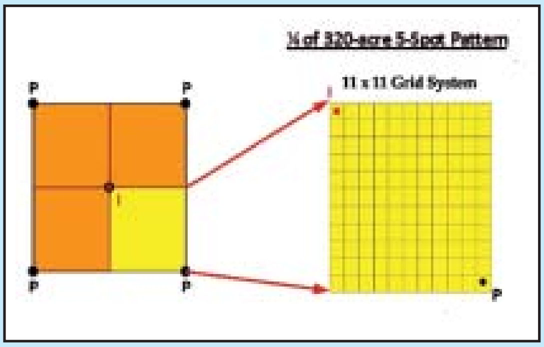


Figure 4
Schematic diagram of rectangular grid system

where k_0 and σ_0 are the cleat permeability and the effective stress at initial reservoir pressure p_0, and c_f is the cleat volume compressibility with respect to changes in the effective horizontal stress ($\sigma - \sigma_0$) normal to the cleat, σ is the volumetric shrinkage/swelling coefficient (kg/m^3), $V(p)$ is the remaining gas content (m^3/kg) at reservoir pressure p, and V_0 the initial gas content at p_0. E and ν are Young's Modulus and Poisson's ratio of the coal matrix respectively.

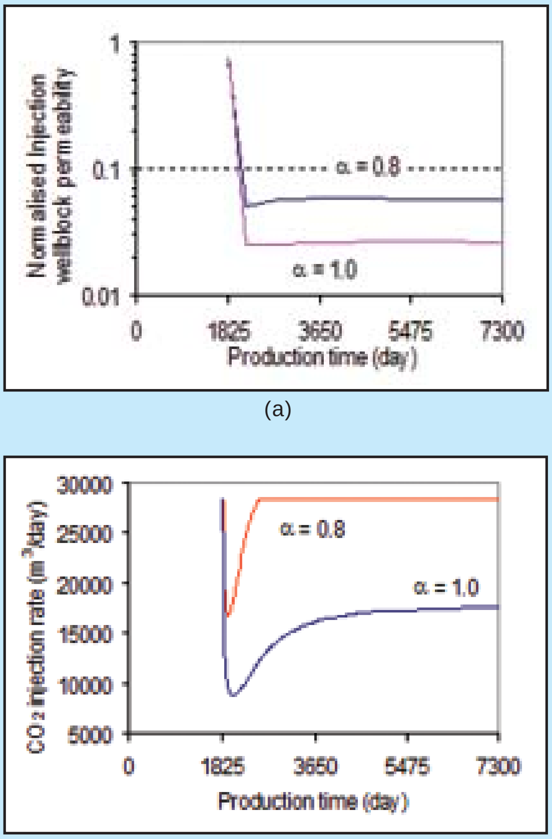
If we further assume that coal matrix shrinkage/swelling associated with desorption/adsorption of a gas mixture is proportional to the net volume of gas desorbed/adsorbed, Equation (5) may be expanded, for a n-component gas mixture, to

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E\alpha}{3(1-\nu)}\left(\sum_{j=1}^{n} \mathrm{V}_j - \sum_{j=1}^{n} V_{j0}\right) \tag{6}$$

where V_j is the volume of adsorbed gas for component j, m^3/kg.

Equations (4) and (6) can be used to give a first-order estimation of permeability variation with pore pressure and gas composition in a coalbed reservoir subject to uniaxial strain conditions. The second term in the right hand-side of Equation (6) is referred to as the matrix shrinkage/swelling term. The equations, in conjunction with the extended Langmuir isotherms, have been implemented in our in-house ECBM simulator LEMIGAS [Syahrial, 2005].

Aiming to gain insight into the influence of matrix swelling on the performance of enhanced CBM recovery/CO_2 sequestration, a numerical simulation study was carried out. For modeling purposes, published coalbed reservoir data representative of the Allison Pilot in the San Juan Basin Fruitland formation, which is the only field CO_2 injection data currently available, was used [Reeves, 2002]. Methane production from a coalbed reservoir with 320-acre well spacing over a 20-year period was simulated. It was assumed that the initial free gas phase in the cleat was 90% CH_4 and 10% CO_2. The production and injection wells are situated at blocks (11, 11) and (1, 1) respectively on a 11 x 11 grid, which represents a quarter of a 5-well pattern as shown in Figure 4. After 5 years of primary recovery, CO_2 gas injection at a prescribed rate of 28,300 m^3/day was scheduled at the start of year 6. To prevent hydraulic fracturing, the maximum bottomhole pressure allowed was 15 MPa in the simulation. This implies that the prescribed injection rate may not be maintained all the time.



(a)

(b)

Figure 5
Variations in the injection wellblock permeability and CO_2 injection rates

Figure 5a illustrates the permeability variation of the injection wellblock for the two cases (α = 0.8 and 1.0 kg/m^3, which were obtained by history matching the published field permeability data during primary recovery). It can be seen that the permeability has plunged by more than one order of magnitude shortly after the start of injection. The normalised (against the initial reservoir permeability) absolute permeability of the wellblock then remains largely unchanged at approximately 0.06 (α = 0.8) and 0.03 (α = 1.0) respectively. The effect of CO_2 injection on well injectivity is of particular interest since field evidence at the Allison pilot in the San Juan Basin sug-

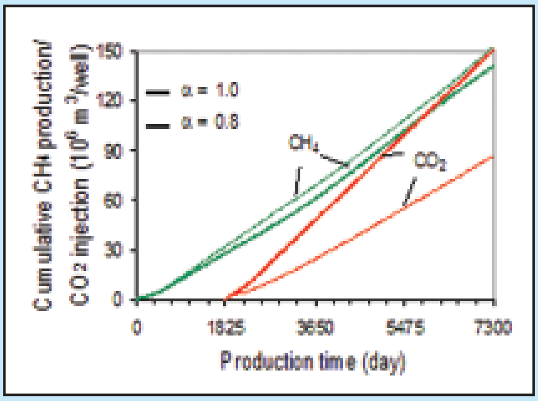


Figure 6
The effect of matrix swelling coefficient on the cumulative CH_4 production and CO_2 injection

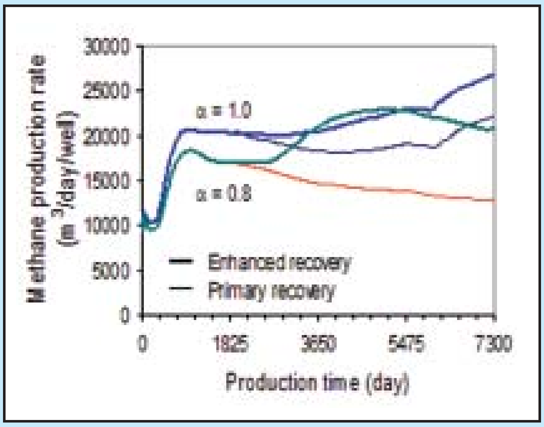


Figure 7
The effect of matrix swelling coefficient on the enhanced recovery

gests that the well injectivity has declined at the early stages of CO_2 injection and then rebounded [Reeves, 2002]. The numerical results shown in Figure 5b are consistent with the above field observation. The results indicate that the magnitude of the matrix shrinkage/swelling coefficient has a profound impact on well injectivity. At $\alpha = 0.8$, the injection rate is able to recover completely after an initial sharp dip, whereas only a partial (approximately 50%) recovery in the injection rate could be achieved when α is increased to 1.0. Given that the absolute permeability of the injection wellblock remained practically constant in the same period, the recovery in the well injectivity appears to be due primarily to a continuing increase in the total mobility of the fluid in the wellblock.

The extreme reduction observed in the well injectivity for the case $\alpha = 1.0$ suggests that the coalbed is less than optimal for CO_2 sequestration under the given reservoir conditions. As shown in Figure 6, approximately 87 million m^3 of CO_2 gas, compared to 150 million m^3 for the case $\alpha = 0.8$, has been injected into the coalbed over the 15-year period, a reduction of more than 40%. It is interesting to note that the cumulative CH_4 production in the two cases are much closer. This implies that the improvement in methane recovery is less pronounced in the case of $\alpha = 1.0$ than for $\alpha = 0.8$, as illustrated in Figure 7.

VI. CONCLUSIONS

A field permeability model for enhanced methane recovery and CO_2 sequestration, incorporating the findings of the current laboratory tests has been developed. The impact of matrix shrinkage/swelling on the production performance on primary and echanced recovery has been observed. It can be concluded that CO_2 injection could result in more than an order of magnitude reduction in the formation around the injection well, and thus a sharp, often prompt decline in well injectivity. The subsequent rebound in injectivity may be due primarily to increased reservoir fluid mobility around the injection well.

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