Swelling of Coal in Response to CO₂ Sequestration for ECBM and Its Effect on Fracture Permeability


Summary
The “swelling” of coal by a penetrant refers to an increase in the volume occupied by the coal as a result of the viscoelastic relaxation of its highly crosslinked macromolecular structure. Projects relating to CO₂ sequestration in coal seams suffer a serious setback in terms of injectivity loss resulting from the swelling of coal. Volumetric swelling associated with CO₂ sorption on coal has a significant influence on the fracture porosity and permeability of the coal. Two coal samples differing in rank were used for volumetric strain measurements. With CO₂, the high-rank Sellar Cornish coal showed a maximum volumetric strain of 1.48% corresponding to an average pore pressure of 13 MPa. A matrix swell-nish coal showed a maximum volumetric strain of 1.9% corresponding to a mean pore pressure of 14 MPa. The effect of permeability variation on the same Warndt Luisenthal coal core shows higher volumetric strain values for all pressure steps. A volumetric strain of 1.9% corresponding to a mean pore pressure of 14 MPa was measured. This confirms the process of sequential swelling.

A unique feature of this work is that real-time permeability measurements were done under unconstrained conditions. Permeabilities were measured, reducing the pore pressure from 16 to 1 MPa at constant flow rate. Although measured permeability increased with increasing pore pressure under unconstrained swelling, in-situ permeability will actually decrease because of fracture closure in a constrained coal. To validate the permeability swelling relationship, both permeability measurements under unconstrained conditions and volumetric strain measurements were used.

Introduction
Maturation of coalbed methane (CBM) production operations in some basins, the emergence of injection schemes for enhanced coalbed methane (ECBM), and carbon sequestration of greenhouse gases has led to renewed focus on the behavior of coalbed reservoir properties under these conditions.

Cleat permeability of coal is the most important parameter for coalbed methane production. Being normal to the bedding plane and orthogonal to each other, the face and butt cleats in coal seams are usually subvertically oriented. Thus, changes in the cleat permeability are primarily controlled by the prevailing effective horizontal stresses that act across the cleats, rather than the effective vertical stress, defined as the difference between the overburden stress and pore pressure (Harpalani and Chen 1997). Coal swelling accompanying CO₂ sorption would decrease the permeability of the coal as the volume increase is compensated within the fracture porosity.

Field evidence suggests that the well injectivity has indeed declined at early stages of CO₂ injection. It has been reported that on a unit of pressure basis, CO₂ causes more swelling than CH₄ (i.e., 20 cm³/g of CO₂ causes more swelling than 20 cm³/g of CH₄) (Pekot and Reeves 2002). This differential swelling behavior would have extreme consequences for field-injection projects. It may lead to elevated injection pressures, causing uncontrolled fracturing of the reservoir beyond a certain pressure. The detrimental effect of matrix swelling on cleat permeability is envisaged in this work. Also, the relationships between concentration, strain, pressure, and swelling of coal matrix are studied.

A series of volumetric swelling experiments by Chikatamarla et al. (2004) using N₂, CH₄, CO₂, and H₂S were carried out on Canadian coals to access the permeability damage.

Swelling/shrinkage coefficients have been reported in different units by different authors. Seidle and Huitt (1995) calculated the swelling coefficients, assuming the swelling to be proportional to the amount of gas sorbed and relating the sorbed gas to pressure by the Langmuir equation. The strain in the coal caused by the mechanical deformation was deducted from the obtained “sorption” strain, and this value was then used to calculate the swelling coefficient. The concept of mechanical strain in coals is explained later in this article. Seidle and Huitt (1995) reported the swelling coefficient in dimensions of microstrain–ton/Scf.

Other authors have calculated the shrinkage/swelling coefficients after Levine (1996) by using a Langmuir-type equation. They assume that the shrinkage/swelling coefficient is a measure of strain with a change in pressure. This was assumed because the pressure vs. strain curve follows the trend of an isotherm. The values reported by all other authors are in dimensions of MPa⁻¹. The swelling coefficients reported are all from experiments conducted on coal core or plugs. Table 1 lists the swelling and shrinkage coefficients for CO₂ and CH₄ reported up-to-date by various authors.

Equipment Design
The equipment was designed according to the work plan of the experiments. Therefore, it is necessary to explain the work scheme:

1. Determine the mechanical compliance of the coal core as a function of mean pore pressure using helium. The effective stress (Pₑₓₑ) was kept constant while changing the pore pressure. Effective stress or effective pressure is the difference between the outside mechanical stress and the pore pressure.

2. Determine the absolute swelling of coal with CO₂ as a function of the mean pore pressure and constant Pₑₓₑ. To establish the matrix swelling effect alone, the mechanical effect measured from Step i has to be subtracted.

3. Estimate and establish the dependence of permeability on mean CO₂ pore pressure. The effect of permeability variation caused by change in Pₑₓₑ is removed by keeping the effective pressure (Pₑₓₑ) constant over the whole course of the experiment.

The uniqueness of these experiments, using large cores, makes the design of the setup complex. A high-pressure coreflood setup was constructed. The pressure cell can reach a maximum confining pressure of 50 MPa. The confining pressure, which can be otherwise stated as the outside mechanical stress, was exerted by means of hydraulic oil. During the course of the experiment, this confining pressure was controlled manually so as to set the required effective stress. For each pressure step, the expected pore
pressure was calculated, and then the confining pressure was added manually by means of a pressure-actuated valve to keep the effective stress ($P_{\text{eff}}$) constant throughout the course of the experiment. The confining pressure was applied on the coal core inside a rubber sleeve. To prevent the gas from diffusing through the rubber sleeve, a lead foil was wrapped around the coal core. To simulate downhole conditions, the temperature in the pressure cell was maintained at 45°C. The sample diameter is 72 mm. The length of the core varied from sample to sample. For the first experiment, a high-rank coal core of 268 mm in length was used, and for the second and third experiments, a low-rank coal core of 154 mm in length was used. To avoid mechanical end effects on the core permeability, two si-perm plates are fixed at either ends of the core. The injection and production tubings were attached to the end plates. These si-perm plates have a porosity of 33% and a permeability of $10^{-13}$ m$^2$. The schematic of the setup is shown in Fig. 1.

Strain gauges were attached on the sample surface to measure the sorption-induced volumetric strain in the coal. The procedure followed is explained in the following section. The strain measurements were stored, through an amplifier and a data acquisition system, into a computer. A mechanical displacement transducer (LVDT) measured the axial changes in the sample dimension throughout the course of the experiment.

A reference vessel outside the reactor was used to feed the gas. The gas was charged to this reference vessel by an ISCO pump. Then the gas was boosted into the reference cell to get the required pressures. Time was needed to stabilize the temperature in the reference cell.

Permeability measurements were carried out during the experiment with each decreasing pressure step. The ISCO pump was used to inject the gas at a constant rate. The average of the injection and production pressure was taken as the core pressure for the calculation of the permeability. A digital flowmeter unique to measure CO$_2$ flow was used at the production end to monitor the flow rate. When no change in flow rate was observed over a period of 1 hour, the flow was considered to be stable. Usually, the flow stabilized between 12 and 30 hours after the start of injection. Considering the fact that the desorbing gas was also contributing to the production stream, up to a maximum of 48 hours was given for the flow to stabilize. At the production end, a backpressure valve was used to control the flow out. CO$_2$ was used to measure the permeability.

### Sample Description and Preparation

The samples used for these experiments were from the South Wales coal field (Selar Cornish) in the U.K. and the Warndt Luisenthal coal field in Germany. The details of the samples are shown in Table 2. The samples selected were quite diverse in their rank and internal properties.

First, a part of the coal core surface, smoothed free of cleats, was selected. If needed, the representative surface was polished. So that the strain gauges did not come off the surface because of

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**Table 1:** The swelling and shrinkage coefficients for CO$_2$ and CH$_4$ reported till date by various authors

<table>
<thead>
<tr>
<th>Shrinkage Coefficient ($C_n$)</th>
<th>Gas Type</th>
<th>Unit</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5(10$^{-3}$)</td>
<td>CO$_2$</td>
<td>MPa$^{-1}$</td>
<td>Reucroft and Patel (1986)</td>
</tr>
<tr>
<td>2.39(10$^{-3}$)</td>
<td>CO$_2$</td>
<td>MPa$^{-1}$</td>
<td>Zutshi and Harpalani (2004)</td>
</tr>
<tr>
<td>5.19(10$^{-3}$)</td>
<td>CO$_2$</td>
<td>MPa$^{-1}$</td>
<td>George and Barkat (2000)</td>
</tr>
<tr>
<td>4.0-10.0(10$^{-4}$)</td>
<td>CH$_4$</td>
<td>MPa$^{-1}$</td>
<td>Gunther (1968)</td>
</tr>
<tr>
<td>2.03-10.0(10$^{-4}$)</td>
<td>CH$_4$</td>
<td>MPa$^{-1}$</td>
<td>Wubben et al. (1986)</td>
</tr>
<tr>
<td>1.25(10$^{-4}$)</td>
<td>CH$_4$</td>
<td>MPa$^{-1}$</td>
<td>Gray (1987)</td>
</tr>
<tr>
<td>3.72(10$^{-2}$)</td>
<td>CH$_4$</td>
<td>MPa$^{-1}$</td>
<td>Juntgen (1990)</td>
</tr>
<tr>
<td>8.99(10$^{-4}$)</td>
<td>CH$_4$</td>
<td>MPa$^{-1}$</td>
<td>Harpalani and Scraufnagel (1990)</td>
</tr>
<tr>
<td>1.3(10$^{-4}$)</td>
<td>CH$_4$</td>
<td>MPa$^{-1}$</td>
<td>George and Barkat (2000)</td>
</tr>
<tr>
<td>11.99(10$^{-4}$)</td>
<td>CH$_4$</td>
<td>MPa$^{-1}$</td>
<td>George and Barkat (2000)</td>
</tr>
<tr>
<td>2.47(10$^{-4}$)</td>
<td>CH$_4$</td>
<td>MPa$^{-1}$</td>
<td>Moffat and Weale (1995)</td>
</tr>
</tbody>
</table>

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**Fig. 1:** Schematic of the entire setup.
the shear force of the rubber sleeve, grooves approximately 2 mm deep were made. The groove surfaces were also polished. The bonding area was cleaned with industrial tissue paper or cloth soaked in a small quantity of chemical solvent such as acetone. It was cleaned until a new tissue or cloth came away completely free of coal particles. If the surface is left uneven, the strain gauges will not adhere properly to the surface. Then the adhesive to be used for fixing the strain gauges on the coal surface was prepared. The adhesive was applied evenly on both surfaces (i.e., on the strain gauge surface as well as the coal surface). A polyethylene sheet was placed onto it and pressed down on the gauge for approximately 10 minutes. Connectors were positioned at a distance of 3 to 5 mm from the gauge. The junction area was soldered for both the gauge leads and the connecting terminals. To connect the extension, the lead wires were soldered to the connecting terminals. Two strain gauges were axially oriented, and the two others were radially oriented on the core surface. Copper wires of sufficient length were soldered to the terminals of each of these strain gauges. A groove was made along the length of the core, and the wires were guided through this groove. All the grooves were then filled with a mixture of coal puff and the adhesive. This further prevented the strain gauges from being sheared off the surface during the experiment.

The strain gauges were of the rosette type (TML-PC-10), with a gauge factor of 2.07. The strain gauges had an accuracy of +/-2%. The gauge factor can be defined as follows:

\[ k = \frac{\Delta R}{R} \]

\( \Delta R/R \) is indicated by specifying the Poisson’s ratio of the test specimen. The gauges were connected to a (1/4) Wheatstone bridge, whose amplifier output is given by

\[ e = \frac{4A_{op}}{k \mu A} \]

With this arrangement, the axial and radial strain in the coal sample caused by swelling induced by the sorption of CO\textsubscript{2} was measured. The directional placements of the strain gauges were done so as to measure the two horizontal strains (strain parallel to the bedding plane). Because the natural fracture system in coal (cleats) is disposed perpendicular to the bedding plane, it is the horizontal strain that is involved in permeability change taking place because of the swelling of the coal matrix.

**Sorption-Induced Absolute Swelling Experiments**

The setup was designed to measure volumetric strain caused by changes in sorbed gas concentration while keeping the net stress on the coal sample constant. The tests start with a complex procedure of mounting the coal core sample in a rubber sleeve and building it in the high-pressure cell (leak-free). The sample cell was connected to a vacuum pump for at least a week to eliminate any form of residual gas or moisture. Prior to the start of the experiment, strain gauges were calibrated for temperature variations.

A mechanical compliance test with helium is almost compulsory at the start. Helium was injected in the coal in 20-bar steps of increasing pressure up to 160 bar. The effective pressure (\( P_{\text{eff}} = P_{\text{pore}} - P_{\text{am}} \)) was kept constant throughout the experiment. The pressure was reduced in a similar way. Each injection cycle ended after an equilibration time of 30 minutes. This test was done to measure the void volume of the setup and to estimate the mechanical compliance coefficient of the coal (Seidle and Huitt 1995). Helium was selected because of its nonsorbing nature to the coal surface. Thus, the measured strain with helium is solely caused by the mechanical compression of the solid coal resulting from the change in pressure.

The next set of experiments were done to determine the absolute swelling of coal with CO\textsubscript{2} as a function of the mean pore pressure and constant \( P_{\text{ref}} \). Here, CO\textsubscript{2} was used instead of helium. The CO\textsubscript{2} sorption experiment was carried out at 45°C. The confining pressure was maintained on the sample with hydraulic oil. The pore pressure, \( P_{\text{pore}} \), was increased in increments of 20 bar until the end pressure of 160 bar was reached. After each pressure step, an equilibration time of 4 to 7 days was given. Over the entire course of the experiment, the effective pressure, \( P_{\text{eff}} \), was kept constant. Measurements are made for the strain in the system. Three experiments were performed, one with the Sellar Cornish coal and two with the Warndt Luisenthal coal. The third experiment was a repetition of the second experiment. At the end of each experiment, the core was built out, the length of the sample measured, and the integrity of the coal checked. For all three experiments, the position of the strain gauges was checked for slip, but was found to be intact. No independent evidence of deformation was recorded.

**Data Analysis.** The axial and the radial strains were obtained from the strain gauges fixed on the sample. Strain-gauge response from the repeat Warndt Luisenthal experiment is shown in **Fig. 2.** Assuming isotropic swelling, we have

\[ \epsilon_{\text{volumetric}} = \epsilon_x + 2\epsilon_y \]

Following the helium injection, the volumetric strain response of the coal sample was used to calculate the mechanical compliance coefficient (\( C_p \)). \( C_p \) is defined as the strain change with corresponding change in pressure and is primarily caused by grain compression.

\[ C_p = \frac{d \epsilon_v}{d P} \]

Methane and carbon dioxide sorption data can be modeled using the empirical form of the Langmuir isotherm model (Levine 1996). Therefore, an equation having the same mathematical form as the Langmuir equation was used in this study to fit the sorption strain data theoretically, as depicted in the next section.
Matrix swelling coefficient is a measure of the strain change with pressure-dependent, but while comparing different samples, $C_p$ was estimated by best fitting a linearized form of Eq. 5 where $e/P$ is plotted against $e$. The slope of this linearized form is equal to $1/P_m$ and the $y$-intercept is equal to $e_{max}/P_m$. Matrix swelling coefficient is a measure of the strain change with the corresponding change in pressure.

$$C_m = \frac{ds}{dP} = \frac{(e_{max} P_m)}{(P_m + P)^2} \quad (6)$$

The coefficient derived from this equation has the unit of MPa$^{-1}$, which quantifies the change in volumetric strain per unit pressure.

**Results and Discussion.** The first part of the experiment is a mechanical compliance test for the coal core samples by injecting helium in pressure steps of 20 bar and continuously monitoring the strain. The sample was considered to be in equilibrium if the strain remained constant for more than 30 minutes. Because helium is not sorbed onto coal, no swelling of the coal matrix occurs, and the entire strain observed is because of the compression of the coal matrix by the increasing gas pressure. The mechanical compliance test results are shown in Figs. 3 and 4. The linearity of the compression with pressure is quite evident. This effect is subtracted to get the volumetric strain because of the sorption of CO$_2$. The mechanical compliance coefficient ($C_m$) for the Selar Cornish and the Warndt Luisenthal coal were calculated to be $-5.0 \times 10^{-4}$ MPa$^{-1}$ and $-1.0 \times 10^{-4}$ MPa$^{-1}$, respectively. Various values of $C_m$ have been reported by various authors. This holds true because $C_m$ is a rank-dependent property of coal. For the same sample, $C_m$ is pressure-dependent, but while comparing different samples, $C_m$ is rank-dependent as well.

In the second series of experiments with CO$_2$ injection, we recognized a combined effect of grain compression and matrix swelling. The volumetric strain results from the three experiments are shown in Figs. 5 through 7. The effect of swelling was singled out by subtracting the mechanical effects. As can be seen from the volumetric strain results, matrix swelling is more dominant. Fig. 5 shows the experimental and the theoretical volumetric strain measurements of the Selar Cornish coal. During this experiment, the effective pressure ($P_{eff}$) was kept constant at 4 MPa. With CO$_2$, the Selar Cornish coal showed a maximum volumetric strain of 1.48% corresponding to an average pore pressure of 13 MPa. A matrix swelling coefficient ($C_m$) of $1.77 \times 10^{-4}$ MPa$^{-1}$ was calculated from this experiment. Similarly, the experimental and theoretical volumetric strain measurements of the Warndt Luisenthal coal are shown in Figs. 6 and 7. Fig. 7 shows a repeat experiment, conducted on the same coal sample as the experiment shown in Fig. 6. The low-rank Warndt Luisenthal coal exhibited a higher strain of around 1.6% compared to the high-rank Selar Cornish. Thus, the rank dependence of swelling holds true for this set of experiments. The repeat Warndt Luisenthal experiment showed higher volumetric strain values for all pressure steps. A maximum volumetric strain of 1.9% corresponding to a mean pore pressure of 14 MPa was measured. This confirms that the process of sequential swelling is in accordance with the observation, as suggested by Bodily et al. (1989). Sequential swelling confirms the highly crosslinked macromolecular nature of coal. It also suggests that the swelling of coal by all nonpolar gases such as CO$_2$ and CH$_4$ is caused by the dispersion force interaction between the gas and the coal macromolecular network. The crosslinks broken at the first place are not completely reformed upon removal of the sorbent leading to incremental strains, as shown in the repeat experiment. Sequential swelling is proposed to explain the incremental strain observed from the repeat experiment. More experiments are presently being conducted to prove the fact.
The matrix swelling coefficients ($C_m$) from the two Warndt Luisenthal experimental samples are $8.98 \times 10^{-5}$ MPa$^{-1}$ and $7.92 \times 10^{-5}$ MPa$^{-1}$, respectively. The matrix swelling coefficients for the low-and high-rank coal differ by an order of magnitude. For all three experiments, the actual value of $C_m$ varied, and was lower for gas pressures greater than 4 MPa and higher for gas pressures lower than 4 MPa. This was also reported by George and Barkat (2001). For the Selar Cornish coal, an end strain of $-0.45\%$ was measured, and for the Warndt Luisenthal coal an end strain of $-0.92\%$ was measured.

The curvature nature of the experimental strains are probably attributable to short equilibration times or the heterogeneity in the coal. Fig. 2 demonstrates the strain change with time for the repeat Warndt Luisenthal experiment. Inertinite rich bands in the core do contribute to the volume, but do not adsorb the same as the bright vitrinite bands. Fig. 2 shows that reaching equilibrium in terms of strain measurement over all individual strain gauges was not possible. But the criterion for continue doing the next step was based on the equilibration of the pressure over time. When the change in pressure was observed to be less than 0.01 MPa over 12 hours, the experiment was ready for the next step. Moreover, the nonequilibrium in the strain measurement (Fig. 2) is only observed in one pair of axial and radial strain measurements, which were coupled together at one particular point on the coal core. Considering the scale of the samples it is quite possible that a particular location on the coal surface cannot be absolutely free of micro/meso cleats. The presence of such minor fractures will obviously affect the equilibrium strain measurements. The bad fit between the theoretical and the experimental strain may otherwise suggest that a Langmuir-type model is not enough to describe the process. A more mechanistic model is needed for this purpose.

The swelling experiments show that the transport process in coal is complex. The similarities in structure between coal and glassy polymers have led to the application of theories of sorption behavior of polymers to coals. During diffusive transport at low or moderate temperatures, as gas enters the macromolecular network of coal, the network density decreases. It results in an increase of the large molecular chain motions (Peppas and Ritger 1987). This increase of the gas concentration of the network can be considered as an effective decrease of the glass transition temperature. Structural changes induced during this process include swelling, microcavity formation, and primary-phase transition requiring rearrangements of each chain segment. Such changes are dominated by relaxational phenomenon.

The diffusion of gas into glassy polymers may vary between two analytically treatable extremes. If the diffusion is controlled by the concentration gradient between the center and the outside of the particle, the diffusion mechanism is Fickian. The diffusion in glassy polymers often does not fit the Fickian diffusion model. Alfrey et al. (1966) presented a second limiting case for sorption. Here, the rate of transport is entirely controlled by molecular relaxation. This type of transport mechanism is designated as Case II transport. Thomas and Windle (1982) proposed that the rate-controlling step at the penetrant front is the time-dependent mechanical deformation of the glassy polymer in response to the thermodynamic swelling stress. A stress-driven anomalous diffusion process of CO$_2$ in coal has been discussed by Mazumder et al. (2006).

**Effect of Matrix Swelling on Fracture Porosity and Permeability**

The coal matrix is heterogeneous and is characterized by two distinct porosity systems: micropores and macropores. The macroporosity in coal consists of the cleats. It is a well-defined and uniformly distributed network of natural fractures. The cleat system can be subdivided into continuous and discontinous butt cleats, which terminate at intersections with the face cleat.

Cleat permeability is recognized as the most important parameter for coalbed methane production. Being normal to the bedding plane and orthogonal to each other, the face and butt cleats in coal seams are usually subvertically oriented. Changes in cleat permeability are primarily controlled by the prevailing effective horizontal stress that acts across the cleats.

The impact of increasing triaxial stress on permeability of coal samples has been investigated by a number of researchers (Somerton et al. 1975; Durucan and Edwards 1986). Experimental measurements indicate that permeability of coal decreases exponentially with increasing effective stress ($P_{ef}$) (McKee et al. 1987).

The permeability of the cleat structure in coal changes because:

1. The phase relative permeability effects, whereby the degree of saturation will affect the gas and water relative permeabilities of the reservoir.

2. The permeability varies by a change in the effective stress within the seams. The effective stress tends to close the cleats and reduce permeability. It is likely that the permeability is related particularly to the “effective horizontal stress” (Gray 1987) across the cleats because these appear to conduct the most seam fluids. The “effective normal stress” is referred to as the total stress normal to the cleat minus the fluid pressure within the cleat. Under field disposition, the “effective normal stress” can also be termed as the “effective horizontal stress” (Shi and Durucan 2003) because the cleat system is subvertically oriented to the bedding plane and its subdivisions are orthogonal to each other. Under these circumstances, the permeability variations brought about by variations in fluid pressures are anisotropic, depending on the nature, frequency, and direction of the cleats. Such opening and closing of the cleats is also likely to change the phase relative permeabilities and capillary pressures within the coal.

3. The permeability varies because of shrinkage while methane is being desorbed, or swelling while carbon dioxide is being injected. This aspect of permeability variation is being dealt with.

The test procedure in the laboratory involved confining a 20-cm-long and 7-cm-diameter coal core sample under a number of isotropic stress levels in the cell and injecting carbon dioxide through the sample at a steady pressure until the flow came to equilibrium. Twelve to 48 hours were required to reach equilibrium. Because gas pressure varied across the sample, the average of the two end gas pressures was used in the calculation of the effective stress. The equation below was used to calculate the core permeability (Gray 1987).

$$k = \frac{2qP_f \mu_d}{A(P_{ef} - P_e^0)}$$

The permeability measurements were conducted on the Selar Cornish and the Warndt Luisenthal coal core samples. The coal samples used had high cleat density. At the end of the absolute swelling measurements with CO$_2$, when the coal core reached equilibrium at pressures greater than 14 MPa, the permeability measurements were carried out at each step of decreasing pressure.

For all measurements, the cell was kept at a constant temperature of 45°C. As shown in Fig. 1, the pressure vessel is a biaxial cell where the coal core is placed inside a rubber sleeve. The effective stress during the entire experiment was maintained around 4 MPa for the Selar Cornish coal and around 6 MPa for the Warndt
Luisenthal sample. After the stress stabilized, the injection of CO₂ was performed with the ISCO pump at a constant rate. A digital mass flowmeter specially calibrated for CO₂ was used to measure the flow on the production end. To keep the downstream pressure constant and to create a pressure gradient, a backpressure valve was used. The flow measurements for a particular pressure step were only used when all equilibrium conditions were satisfied. Performing the first permeability measurement at higher pressure ensured that the coal core sample equilibrated both in terms of its sorption capacity and of sorption-induced swelling. This arrangement does allow the coal to swell to its maximum under the respective mean pore pressure and the applied effective stress, and this can be better referred to as unconstrained swelling. The swelling of coal matrix caused by injection results in a change in the cleat porosity and, therefore, the cleat permeability. Under ideal field conditions, the coal seam is not allowed to swell beyond its boundaries in both the vertical and horizontal directions. The complete effect of volumetric strain will thus be translated in terms of reduction in cleat porosity.

**Results and Discussion.** The results of the permeability measurements in the laboratory are shown in Figs. 8 and 9. Under stress, both the coal samples have extremely low initial permeability in the range of 0.01 md. The slight variation in the effective stress ($P_{eff}$) at lower pressures was unavoidable. Because the coal core was free to swell inside the pressure cell (unconstrained swelling), the measured permeability is higher at higher mean pore pressure, and vice versa. This whole process of free swelling in the laboratory in comparison to constrained swelling in the field is analogous to thermal expansion (Shi and Durucan 2003). A hollow steel pipe subjected to thermal expansion encounters an increase in its free volume, which is analogous to an increase in the cleat porosity with increasing swelling in our case. Stress-strain relationships for coal as a thermoelastic porous medium are described by Shi and Durucan (2003). They have modeled this process by which they have replaced the thermal expansion term with an analogous swelling term.

To understand why the permeability of the coal core increase with increasing pore pressure ($P_{pore}$) while the effective stress is kept constant is a question of understanding what swelling stress ($\sigma_{sw}$) is. Swelling stress is defined as the pressure of an element of coal matrix saturated with the adsorbent (CO₂/CH₄/N₂) avoiding at the same time deformation. The very definition makes it clear that the measurement, or measurement methodology of swelling stress, is not a matter to be easily accomplished. From the viewpoint of thermodynamics, swelling stress represents a kind of energy. In the case of free swelling (unconstrained laboratory conditions), it turns out to be a volume change. Swelling stress only occurs in the case of constrained swelling. The concept of swelling stress is shown in Fig. 10. Considering a deformed domain, a process of back compaction can be visualized to understand the swelling stress. With the present experimental setup, a case of free swelling will result in a volume change ($dV$). This volume change will see an incremental rise in the annular pressure ($P_{ann}$) of the cell. But because the system is set so as to keep the effective stress ($P_{eff}$) constant, some of the oil from the annular space will drain out.

There are two sets of experimental data to validate a relationship between permeability and swelling: permeability measurements under unconstrained conditions, and volumetric strain measurements.

Using the experimentally determined permeability measurements under unconstrained conditions (Figs. 8 and 9) and assuming that permeability varies with porosity as follows,

$$\frac{k_{new}}{k_{initial}} = \left( \frac{\phi_{new}}{\phi_{initial}} \right)^{1 - (1 - \phi_{initial})^2} \left( 1 - \phi_{new} \right)^2$$

(8)

changes in cleat porosity were calculated. The increase in coal cleat porosity because of unconstrained swelling is considered to be equal to the decrease in cleat porosity under field conditions with constrained swelling. The resulting decrease in the cleat porosities is shown in Figs. 11 and 12. This assumption is valid when the total volume of coal (matrix and cleats) remains constant with injection of CO₂. With the decrease in cleat porosity calculated and with a set of three different initial porosity values, the permeability variation under constrained condition was determined. Although significant advances have been made, it is still difficult to measure.

**Fig. 8**—Experimentally determined variation in permeability for Sesar Cornish coal as a result of matrix swelling under unconstrained conditions.

**Fig. 9**—Experimentally determined variation in permeability for Warndt Luisenthal coal as a result of matrix swelling under unconstrained conditions.

**Fig. 10**—Concept of swelling stress.
cleat porosity accurately because of the very small volume of cleats in a core. For that reason, a range of three different initial cleat porosity values between 0.1 and 1.0% was used to estimate the change in permeability with sorption-induced swelling. The resulting variations in permeability are shown in Figs. 13 and 14. For all initial porosity cases, the porosity attains negative values, because the initial permeability of the sample is very low. This has also been reported by Zutshi and Harpalani (2004) with a matchstick model.* Under laboratory conditions, the negative permeability can be explained as the flow, which takes place through the coal matrix and can no longer be considered as a fracture or cleat flow. Model-generated negative permeability and porosity lacks any physical meaning. But this retains the essence of the swelling-induced injectivity problem. Negative permeability and negative porosity values indicate near-zero porosity and permeability at those pressures. This problem can be anticipated at field-scale injection projects in low-permeability coal. Thus, injecting under a near-zero permeability condition results in very high bottomhole pressures, which exceeds the fracture breakdown limit, resulting in propagation of uncontrolled fractures.

With the second set of data on volumetric strain measurements and following the procedure described by Harpalani and Chen (1992, 1995, 1997), changes in cleat porosity and permeability, as a result of changing volumes of the coal matrix, were calculated. This procedure, by using the matchstick model (Reiss 1980), is briefly described next. The increase in coal matrix volume caused by swelling was considered equal to the decrease in cleat aperture \( b \) as shown in Fig. 15, assuming that the total volume of coal remains constant upon injection of CO\(_2\). Assuming a matchstick geometry, where \( a_1 = a_2 \), the initial geometry \( \phi_{\text{initial}} \) is given by

\[
\phi_{\text{initial}} = \frac{2}{a} \left( 1 - \frac{b}{a} \Delta \phi \right) \tag{9}
\]

The new cleat porosity can thus be written as

\[
\phi_{\text{new}} = \frac{2}{a} \left( 1 - \frac{b}{a} \Delta \phi \right) \tag{10}
\]

Substituting the value of \( \Delta \phi \), the porosity ratio can be written as:

\[
\frac{\phi_{\text{new}}}{\phi_{\text{initial}}} = \left( \frac{1 - \frac{2}{a} \Delta P / \phi_{\text{initial}}}{1 + \frac{2}{a} \Delta P} \right) \tag{11}
\]

Using estimates for initial porosity and the experimental horizontal strain, pressure-dependent cleat porosity can be estimated and compared to the experimentally derived porosity change. Moreover, the change in cleat porosity by swelling will change the cleat permeability. Similar to the case just presented, the ratio of the modified cleat permeability can be written as:

\[
\frac{k_{\text{new}}}{k_{\text{initial}}} = \left( \frac{1 - \frac{2}{a} \Delta P / \phi_{\text{initial}}}{1 + \frac{2}{a} \Delta P} \right)^3 \tag{12}
\]

The variations in permeability as a function of the initial porosity for both the Selaar Cornish and Warnsdt Luisenthal coal core absolute swelling experiments are shown in Figs. 16 and 17. The permeability variations for both the experiments have been worked out for three different porosity situations as shown in the figures. As expected, the permeability in all three situations decreases to zero. However, these results showing a decrease in permeability are caused by a change in matrix volume alone. In our experiments, the effective stress \( P_{\text{eff}} \) was kept constant. Under true field conditions, the injection of CO\(_2\) would also result in a simultaneous decrease in the \( P_{\text{eff}} \), which would result in an increase in the cleat permeability and would thus counter a part of the permeability reduction attributable to volume increase.

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* Personal communication with Harpalani, 2005.
Conclusions

The major conclusion of this experimental study is that injection of CO₂ in coal seams results in volumetric swelling. This injection has a profound effect on the fracture porosity and permeability of the coal. The rank dependence of swelling was established by performing experiments with two coal samples differing in rank. Sequential swelling of coal holds true and is in line with comparing the coal structure with that of glassy polymers. With the perception of swelling in coal, the transport process should be dealt with in much detail. Decrease in permeability caused by change in matrix volume was studied under constant effective stress conditions. This suggests that CO₂ injection in coal seams could result in serious injectivity problems near the wellbore.

Nomenclature

- \( a \) = the initial cleat spacing, m
- \( A \) = cross-section area, cm²
- \( A_{op} \) = amplifier output, volts
- \( A_c \) = amplification, \( \times 1000 \) in this case
- \( C_m \) = swelling coefficient, MPa⁻¹
- \( C_r \) = mechanical compliance coefficient, MPa⁻¹
- \( k \) = permeability, md
- \( K \) = gauge factor, –
- \( l_m \) = change in dimension of the cleat matrix in the horizontal direction per unit pressure
- \( L \) = length of the core, m
- \( P_{ann} \) = annular pressure, MPa
- \( P_{eff} \) = effective stress, MPa
- \( P_i \) = injection pressure, MPa
- \( P_{pore} \) = pore pressure, MPa
- \( P_0 \) = production pressure, MPa
- \( P_{vp} \) = corresponds mathematically to the “Langmuir pressure” and represents the pressure at which the coal has attained 50% of its maximum strain. The lower the value of \( P_{vp} \), the steeper the sorption curve at low pressures.

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References


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**SI Metric Conversion Factors**

- \( cp \times 1.000 \) \( E^{-03*} \) = Pa.s
- \( ft \times 3.048 \) \( E^{-01*} \) = m
- \( \text{md} \times 9.869 \times 233 \) \( E^{-04} \) = \( \mu m^2 \)
- \( \text{psi} \times 6.8948 \) \( E^{-03*} \) = MPa

*Conversion factor is exact

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