Effect of gas production on porosity and permeability of coal

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ABSTRACT

Coal is a dual porosity rock with the coal matrix consisting primarily of micropores accounting for most of the porosity, and the cleats (macropores) for the permeability of coal to fluids. This paper discusses the results of a laboratory study aimed at measuring the changes in the coal matrix volume with release of gas, and calculating the resulting change in the cleat porosity of coal.

The volumetric strain of the coal matrix with decreasing pressure of methane was monitored, and the variation in the total and cleat porosity was calculated. The results show that the coal matrix volume decreases with desorption as methane pressure decreases and that there is a linear relationship between the coal matrix volumetric strain, and the quantity of gas released. If this shrinkage is greater than the compaction caused due to the increase in effective stress resulting from decrease in pore pressure, then the fracture aperture would increase in size, thus increasing the cleat porosity and hence the permeability of coal.

INTRODUCTION

Typically, coal seams are naturally fractured and contain laterally extensive, closely spaced vertical fractures called face cleats. A less defined set of natural fractures orthogonal to the face cleats, called butt cleats, are also present in most coals. The face cleat is continuous throughout the seam, while the butt cleat in many cases is discontinuous ending at intersection with face cleat. The cleat spacing ranges from about half to a few cms for different coals (Puri et al, 1990). In between these cleats is the coal matrix consisting of an extremely fine structure, and pores varying in size from a few angstroms (10^{-10} m) to over a micrometer. These micropores and macro pores constitute the microporosity and the macroporosity respectively, and explain why coal is known to be a dual porosity rock. While the micropores in the coal matrix account for most of the porosity in coal, the macropores (cleats) are responsible for the permeability of coal to various fluids.

As a reservoir produces, the fluid pressure in the coal decreases. The decrease in pressure has two consequences. Firstly, it results in desorption of gas in the coal matrix. Secondly, the effective stress (difference between the overburden, and lateral, stress and fluid pressure) increases. Conventional reasoning suggests that, since the flow of gas is through cleats and fractures, this increase in the effective stress would lead to compaction of the cleats in coal and reduced dimensions of these flow paths. The permeability of coal would, therefore, decrease and result in lower flowrates.

However, there is evidence from producing fields that the productivity of coalbed methane reservoirs does not decline with time (Zuber *et al.*, 1989). In some cases, it has maintained a constant level for long periods of time - in excess of ten years (Metcalfe, 1991). Although some increase in permeability at low pressure can be explained by the gas slippage effect (Klinkenberg, 1941) resulting from declining pressure, another mechanism is suspected to be responsible for a gradual increase in the permeability of coal with continued production. This is the desorption of gas, a phenomenon unique in a coalbed methane system, and the resulting changes in the coal matrix volume.

The objective of this research investigation is to study the changes in the volume of coal matrix resulting from desorption of gas, and estimate the resulting increase in the cleat porosity.

BACKGROUND

Swelling of coal due to sorption of liquids is a known phenomenon, and has been reported by several researchers (Gregg, 1961; Reucroft, 1986; Green, 1985). Swelling of coal in the presence of an adsorptive gas has also been investigated in the past. Moffat and Weale (1955) reported studying the swelling/shrinkage of coal with adsorption/desorption of methane in order to interpret the sorption isotherms correctly. For pressures up to 150 atm (approximately 2200 psi), the volume of blocks of different coal was reported to increase by 0.2 to 1.6 %. For pressures between 150 and 700 atm, the volume either decreased or remained constant. This could be due to changes in the volume of the solid coal, or the matrix compressibility effect. The study concluded that sorption of gas results in a change in the solid volume.

Swelling of coal in the presence of a gas has also been studied to investigate how the surface area and pore structure of coal are altered when an adsorptive gas is used for these measurements. This was necessitated by the observation that the surface area of coal determined by sorption of carbon dioxide was higher than that obtained using nitrogen (Reucroft, 1983). The usual assumption that an inherent pore structure exists in coal which can be probed by molecules without influencing the coal structure itself was, therefore, suspected.

To determine if there was a change in the volume of coal caused by the presence of carbon dioxide, and the influence of this on surface area measurements, an experimental study was carried out by Reucroft (1986) using bituminous coal samples 1 cm long and 0.4 cm in diameter. At room temperature (25°C) and a pressure of 20 psig, the reported swelling caused by exposure to carbon dioxide was between 0.36% and 1.31%. This work was followed by another study to evaluate the effect of pressure on swelling behavior of typical coals (Sethuraman and Reucroft, 1987). The results indicated that there was negligible shrinkage with exposure of coal to nitrogen and helium. Also, the lower carbon content correlated with higher degree of swelling. Another finding was that the time required to reach equilibrium was less at high pressures. However, for this study

only the change in the specimen length was monitored. Assuming isotropic behavior, the change in the specimen volume was estimated.

A more recent study involved simultaneous sorption and dilatometric studies of coal cubes under the action of carbon dioxide and methane gases at pressures ranging from 70 to 725 psi (Stefanska, 1990). The conclusion of the study was that the sorption-shrinkage for coal and carbon dioxide is reversible, but not for coal and methane system. Also, the degree of swelling of coal was found to depend on its rank and amount of moisture in the coal. This is expected since these two factors affect the sorption capacity of coal.

As apparent from the brief discussion above, almost all of the past work related to coal matrix volumetric strain was carried out primarily to understand and investigate the surface properties of coal. The current study was carried out to investigate the swelling/shrinkage behavior resulting from sorption of gas, and its impact on flow characteristics of coal. Based on the work reviewed, it was felt that the experimental design must consider the following factors:

1) Both radial and axial strains must be monitored. For large samples, at least two, preferably three, sets of strain gauges should be used.

2) The experiment should be carried out for decreasing pressure all the way from the pressure encountered *in situ* to very low pressure.

3) Since moisture content and temperature affect the quantity of sorbed gas, these two factors would also affect the volumetric strain induced by sorption. Moisture content and temperature should, therefore, be carefully maintained at constant levels.

The following sections give a brief description of the work carried out and the results obtained so far.

EXPERIMENTAL DESIGN AND PRINCIPLES

Experimental Specimens

The unique properties of coal place special constraints on preservation and preparation of coal cores (Puri, 1991; Gash, 1991). Coal cores should be kept in contact with water to prevent drying, and contact of coal cores with air should be avoided (Gash, 1991). Also, weathering (drying by exposing to air and heat) alters the structure of coal (Nelson, 1989), and weathered coal should not be used when measuring rock properties of coal. Weathering results in induced fractures, and the measured values of permeability and porosity of such samples may be significantly different. Based on this information, coal was kept immersed in water at all times.

For this experimental study, cores from the San Juan basin and Pittsburgh seam were used.

Volumetric Strain Measurement

Following the procedure recommended by the ISRM (International Society of Rock Mechanics), four or six strain gages were installed on the specimen surface - two each for axial and radial strains, placed 180° apart. A micro-crystalline wax, recommended by the strain gage manufacturer, was used to coat the strain gages for proper operation in moist conditions.

The sample container was kept in a constant temperature water bath throughout the experiment. Maintaining a constant temperature is important because the process of adsorption/ desorption is very sensitive to temperature, and also to perform experiments at *in situ* temperature conditions. A small cylinder containing distilled water was used as a gas humidifier. Moist gas was used because it is more representative of the gas recovered from coalbeds. Another advantage of using moist gas is that it does not alter the moisture content of the sample by picking up moisture from it. The experimental setup is shown in Figure 1. The details of the procedure are given in a previous publication where the sample was subjected to different methane pressures in steps of 200 psi (increasing and decreasing) and volumetric strain was measured for each step (Harpalani, 1990). A

volumetric strain-pressure relationship was thus established for pure methane. However, the technique had two distinct flaws. The measured strain was the total change in the volume resulting from the changes due to the grain (or matrix) compressibility effect (positive with decrease in pressure) and that due to sorption (negative for decreasing pressure). The two components were then separated by assuming that the two effects are purely additive. The second drawback was that the experimental conditions were not representative of the conditions *in situ* because of the absence of stress. The procedure was, therefore, modified to enable conducting the experiments at a constant pressure. This avoided any effect due to the matrix or grain compressibility, and the measured results are an indication of the effect of desorption alone.

The specimen was first saturated with methane at high pressure. The strain was monitored until equilibrium was attained. A plot of strain vs time indicated that it took approximately four months to reach equilibrium. After that, every time some methane was bled out to reduce the methane pressure, helium was injected to ensure that the total pressure remained constant throughout the experiment. Once again, after attaining equilibrium, a sample of gas from the container was passed through a gas chromatograph and the concentration of methane, C, was measured. Using the relationship,

$$C = P_p/P_t$$

where P_t is the total pressure and P_p is the partial pressure of methane, the partial pressure of methane was calculated. A volumetric strain measurement for each methane pressure was thus obtained for reducing concentrations of methane. It should be pointed out here that the presence of helium has no effect on adsorption/ desorption of methane on coal (Puri, 1990).

RESULTS AND ANALYSES

Volumetric Strain of Coal Matrix

Figure 2 shows the change in volumetric strain ($\Delta V/V$) plotted against decreasing gas pressure for helium and partial pressure of methane cycles for a core from the San Juan

basin. The results have been plotted for the decreasing part of the cycle. Only this is of primary interest, because in field modeling the reservoir pressure always decreases. The matrix volume at maximum pressure was considered as the reference point which is analogous to the conditions in a virgin reservoir.

In case of the helium cycle, as the pressure was decreased, the coal matrix volume started increasing. The grain compressibility, c_m, is the slope of the plot for decreasing helium pressure, as shown in upper plot in Figure 2, and is given by:

$$c_m = \frac{1}{V_m}\left(\frac{dV_m}{dP}\right)$$

where V_m is the matrix volume, and dP is the change in applied pressure at both internal

and external surfaces. For this particular type of coal, c_m for wet coal was estimated to be -6.7×10^{-7}/psi.

When the experiment was repeated using methane, the volumetric strain followed a non-linear path at high pressures, and an almost linear path at low pressures with reduction in pressure. Below 700 psi, there was a continuous decrease in the volume of the coal matrix. This can be attributed to the desorption of gas which is significant at pressures below 700 psi, or the critical desorption pressure.

These results are different from those obtained using the initial procedure since the grain compressibility effect is completely eliminated. An example of results using the old procedure is shown in Figure 3. For the part of the experiment using methane, two mechanisms, grain compressibility and matrix shrinkage associated with desorption, influence the matrix volume and the measured results reflect the combined effect of these two acting against each other. To obtain the effect of desorption alone, the volumetric strain from the helium experiment was subtracted from that obtained using methane. This gave the effective shrinkage of the coal matrix and is included in Figure 3 as the lowermost plot. Once again, the assumption was that the grain compressibility and matrix shrinkage compressibility are purely additive.

From the shrinkage plot, shown in Figure 2, pressure at which the shrinkage actually begins was obtained. This value was used in estimating the matrix shrinkage compressibility, c_m*, defined as the rate of change of matrix volume with change in pressure, given by:

$$c_m* = \frac{1}{V_m}\left(\frac{dV_m}{dP}\right)$$

c_m* was calculated to be 7.5×10^{-7}/psi.

Another interesting feature is the similarity between the shrinkage plot shown in Figure 2 and the sorption isotherm obtained for the same coal sample. The two are plotted together in Figure 4. These results suggest a linear relationship between the volumetric strain and the mean concentration of gas in coal. This is shown in Figure 5. The relationship can be expressed as:

$$\frac{\Delta V_m}{V_m} = \beta V_{des}$$

where,

β is a constant depending on the characteristics of the coal type, and

V_{des} is the volume of gas desorbed.

But V_{des} is given by the Langmuir's equation as:

$$V_{des} = \frac{V_L P}{P_L + P}$$

Therefore,

$$\frac{\Delta V_m}{V_m} = \beta \frac{V_L P}{P_L + P}$$

The constant β might, therefore, be used to characterize a particular seam or basin by carrying out adsorption/desorption and volumetric strain experiments on core samples from different locations in the same seam/basin. If β has a reasonably similar value, or falls within a small range, it can be used to obtain volumetric strains, and hence, the matrix shrinkage compressibility, for other areas of interest. Only the sorption isotherms will then be required for samples from these areas. However, this interpolation can not be used for seams with a variable β at different locations.

Effect of Matrix Shrinkage on Cleat Porosity

The shrinkage of matrix volume results in a change in the void volume of the specimen, thus altering its porosity. Assuming that the total volume remains constant, the decrease in the volume of the coal matrix is, in fact, the increase in the cleat volume. From Figure 3, the total shrinkage (ΔV_{matrix}) was known for the sample from the Pittsburgh seam. Using the relationship,

$$\Delta V_{matrix} = -\Delta V_{void},$$

the change in the total void space in the sample was estimated for different pressure levels.

The measured ΔV_{matrix}, when coupled with the total porosity of the sample (measured to be 3.8%), gave an increase in porosity of 4.3%, as shown in Figure 6. But the matrix shrinkage affects the flow behavior by altering the cleats, or the cleat aperture. Hence, only the cleat porosity, rather than the total porosity, should be considered when calculating changes in the porosity. This is difficult since there are no reliable methods available currently for estimating the cleat porosity accurately, although significant advances have been made recently (Gash, 1992). For this study, the water imbibition method, was used. It relies on the assumption that water can only get into the cleats, and involves monitoring the change in sample weight with time, until the the sample can not imbibe any more water. The value of 1.1% obtained for cleat porosity was, therefore, used to calculate changes in the cleat porosity. Using this value, along with the measured ΔV_{matrix}, an increase of 15% in cleat porosity with desorption of methane was estimated, shown as the upper plot in Figure 6.

More recently, the published values of cleat porosity for coals have been in the range of 0.2% to 0.4% (Young *et al.*, 1991; Gash 1992). Using this, along with the measured matrix shrinkage for the San Juan basin, changes in cleat porosity were calculated and plotted as shown in Figure 7. The increase in cleat porosity, for a pressure decrease of 800 psi, is approximately 30%. Since the available coalbed methane simulators are capable of handling dynamic changes in input parameters, this presents an excellent way of providing the laboratory porosity variation data for field use. Usually, information of this nature is very expensive to obtain in the field since it requires multi-well tests (Zuber *et al.*, 1990).

Variation in Permeability

Although there is usually no direct relationship between permeability and porosity, it may be said that higher (interconnected) porosities usually result in higher permeabilities, and that for rock of similar lithology and similar conditions of sedimentation there may exist an approximate relationship between the two parameters (Freeze and Cherry, 1979).

As explained earlier, shrinkage of the coal matrix leads to an increase in the size of the cleat aperture, thus increasing the cleat porosity. Hence, it is expected that with continued desorption, the permeability of coal would also increase. The shrinkage of coal matrix with desorption may not only widen the cleats, but also reduce the effective horizontal stress and possibly lead to a complete loss of horizontal stress, further opening the cleats (Gray, 1987). The flow through the cleats is, therefore, influenced by two opposing changes in permeability. Where shrinkage is less than the compaction forces, the permeability may decrease with production. On the other hand, in case of large shrinkage, the permeability may increase. Therefore, matrix shrinkage can have a significant impact on long term gas production from coalbed methane reservoirs and can be a very important parameter in predicting production.

Another key question that needs to be answered is: at what pressure does the shrinkage of coal matrix begin? In other words, when does the permeability start increasing appreciably. Any increase in permeability at too late a stage in the life of a reservoir would not benefit gas production since the normal abandonment pressure in coalbed reservoirs is around 150 psi (Puri *et al.*, 1990). For example, in case of one of the samples tested, it started at approximately 800 psia (effective shrinkage plot). In another sample from the same basin, shrinkage of coal matrix started at 740 psia, suggesting that the increase could be extremely meaningful. Once this criterion is attained, the magnitude of the change in permeability from the base case is also important, because in

order for the phenomenon to have an impact, the overall change must be significant.

CONCLUSIONS AND FUTURE WORK

Conclusions

The most important conclusion of this study is that the shrinkage of coal matrix with desorption of gas results in a matrix shrinkage compressibility greater than the matrix (or grain) compressibility. A major consequence of the matrix shrinkage is an increase in the cleat (or fracture) porosity of coal. These results suggest that the shrinkage of matrix, and the associated increase in the cleat porosity can increase the permeability of coal significantly. Depending on the stress conditions, this increase can be dramatic and may result in high flowrates over the life of methane producing wells. It is, therefore, recommended that coal matrix shrinkage be considered, along with cleat contraction due to pore volume compressibility, in order to accurately simulate and predict long term gas production from coalbed methane wells.

Future Work

Based on the work discussed in this paper, it is felt that the following aspects of the gas flow characteristics of coal should be investigated further:

1) Carbon dioxide is one of the constituents of natural gas that is found in coalbeds. It is also known to be more adsorptive than methane. Therefore, the effect of desorption on coal matrix volume should be studied using a multicomponent gas mixture (methane, carbon dioxide and nitrogen).

2) The phenomenon of gas desorption is strongly dependent on parameters like moisture content, temperature, etc.. Therefore, it is important to know these parameters accurately for the basins from which the samples are obtained. The experiments should be conducted at *in situ* conditions.

3) More laboratory work needs to be performed in order to quantify both pore volume and matrix shrinkage compressibilities for U.S. coals. These values can then be used to accurately model long term production of gas from a particular basin.

4) Permeability measurements should be made to investigate the extent of influence of the shrinkage phenomenon on flow behavior.

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