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Abouna Saghafi

*CSIRO Energy Technology, Newcastle*

Hoda Javanmard

*CSIRO Energy Technology, Newcastle*

Douglas Roberts

*CSIRO Energy Technology, Newcastle*

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# PARAMETERS AFFECTING COAL SEAM GAS ESCAPE THROUGH FLOOR AND ROOF STRATA

**Abouna Saghafi<sup>1</sup>, Hoda Javanmard<sup>1</sup> and Douglas Roberts<sup>1</sup>**

**ABSTRACT:** Coal seams are compact gas reservoirs and can contain large volumes of methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) which are the main constituents of coal seam gas (CSG). CSG is present in various volumes and concentrations across the mining regions in the coalfields of the Sydney and Bowen basins. The variations in actual gas volumes and relative concentration of these gases in coal could be due to different gas generation/accumulation rates and different adsorption capacity of the coals, but also because of the difference in the sealing capacity of the non-coal sediments enclosing the coal seams. It is postulated that the sealing capacity of the main roof and floor rocks at a coal seam could have a major effect on the volume of gas in place (gas content).

This paper reports some results of an ongoing investigation on the gas flow parameters which affect the sealing capacity and retention of gas in coal reservoirs. The results discussed here concern, in particular, the matrix permeability (or micro permeability) and the diffusivity of the non-coal horizons in the roof and floor of the coal seams. These properties could be limiting factors on the rate of gas escape from a coal formation to the surrounding strata.

## INTRODUCTION

Coal seams are high capacity gas storage media which depending on their adsorption properties and formation depth can retain large quantities of gases such as CH<sub>4</sub> and CO<sub>2</sub> in free and adsorbed phases. Most of the gas in coal is stored in the micro pore system (few nanometre pore size) where it is adsorbed onto the large surface area available in the micro pores. In the macro pore system gas is also stored in free phase, where at high pressures the quantity of stored gas in this phase can also be of importance. The quantity of gas stored in adsorbed phase (or gas content) depends on the pressure exerted by free gas molecules in the pore void volume. Hence, any fall in the free gas pressure would cause desorption of the adsorbed gas and the reduction of the gas content of coal. The desorbed or free gas can then escape from the coal seams to the upper strata and through conduits to the surface.

The origin of gas and its accumulation in coal seams would be affected by the depth. In deep coal seams gas is generally of thermogenic origin where gas had been produced as a by-product of coalification. New accumulation of CH<sub>4</sub> gas in these seams can be as a result of migration. Igneous activities over geological time have also resulted in the injection of CO<sub>2</sub> into these coal seams (Faiz et al., 2007; Embleton et al., 1985; Facer and Carr, 1979). For shallow coal seams (i.e., <300 m), most gas is of biogenic origin. The stable carbon isotopes ratio analyses of CSG from coals from the Sydney Basin show that CH<sub>4</sub> is generated as a result of microbial activities (Faiz et al., 2003). To allow the movement and storage of the methanogenic micro-organism and nutrients the coal seams have to act as a permeable aquifer.

It is expected that for a given coal formation the actual gas content of the coal seams would depend, among other factors, on the rate of gas accumulation within the coal seams and the rate of gas loss through the non-coal strata enclosing that formation. The main source of gas generation/accumulation in shallow seams is through microbial activities and one of the main mechanisms for gas retention is the sealing capacity of the coal formation. This capacity can be expressed in terms of micro flow properties of the roof and floor of the coal formation.

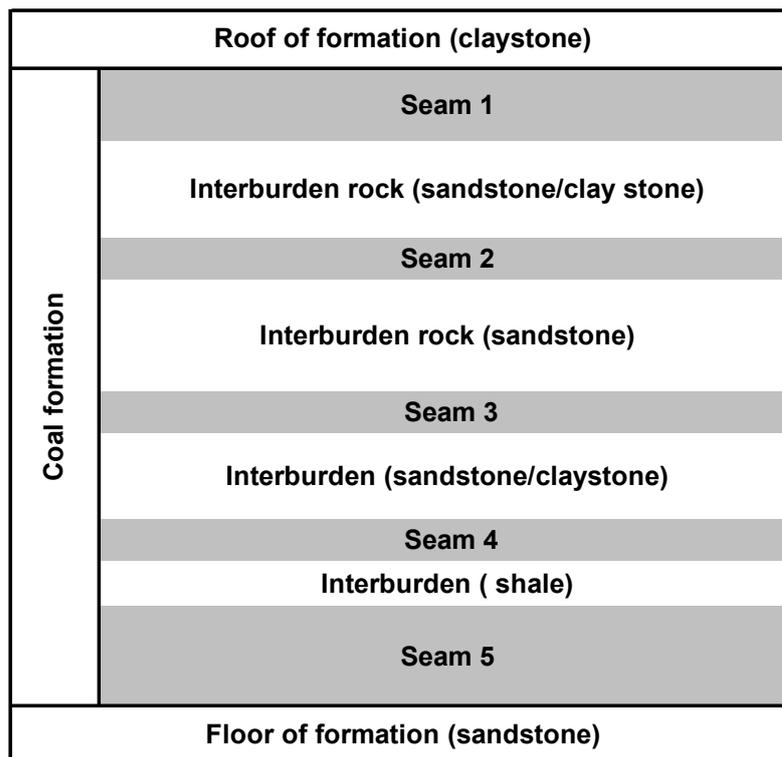
In the next sections the results of a study undertaken to evaluate the sealing properties of non-coal strata in the roof and floor of a coal formation in the Sydney Basin are presented. Coal and rock samples used in this study

The samples for this study were obtained from a coal formation in a coalfield in the Sydney Basin. Roof and floor cores as well as coal samples were collected from an exploration borehole drilled into this coal formation.

<sup>1</sup> CSIRO Energy Technology, Newcastle, NSW 2300

Two major sedimentary rock horizons, a claystone horizon in the roof and a sandstone horizon in the floor, enclose the coal sequences in this coal formation (Figure 1). This formation belongs to a coal system that contains some of the gassiest coal seams of this coalfield. Though the depth of the coal formation at the location of the drilling is relatively close the surface, high gas contents occur in the coal seams at this location. These conditions indicate favourable seal quality of the coal system reservoir. Other parameters may have also contributed to the high gas content such as high rate of biogenic gas generation and high capacity for gas adsorption of the coal; however, this study is limited to the flow properties of the enclosing non-coal strata.

In addition to the roof and floor of the coal formation the interburden rock and carbonaceous sediments were also sampled and are currently being investigated for their micro flow properties. The rock types include shale, siltstone and mudstone.



**Figure 1 - The layout of the coal formation where samples were taken for this study**

## METHODOLOGY

The sealing capacity of non-coal strata may be quantified in various ways. For example, it can be quantified by the time required for the coal system to lose half of its initial stored gas. Any quantification, however, requires the knowledge of the long term behaviour of the coal reservoir in terms of flow properties of the roof and floor units. Note that coal seams can also act as sealing strata.

In order to relate the flow properties of roof and floor rocks to other physical properties that may affect the gas flow within these strata, density and porosity measurement were conducted. The density was measured using a helium expansion method. The mercury intrusion technique was used to measure the porosity for sub-samples taken from roof and floor rocks.

The results of measurements of these properties are shown in Table 1. As is seen these properties are not largely different for the roof and floor samples. Density is higher for the floor sandstone and porosity is higher for the roof claystone.

**Table 1 - Results of density and porosity measurement of floor and roof rocks**

Sample	Porosity (%)	Density (g/c m <sup>3</sup> )
Claystone (roof)	8.80	2.70
Sandstone (floor)	8.20	2.90

### Measurement of micro permeability

As part of this project an apparatus was designed and built to measure the micro permeability of coal and non-coal rocks. It is a modification of a previously built system for the direct measurement of diffusivity of coal (Saghafi, 2001; Saghafi et al, 2007).

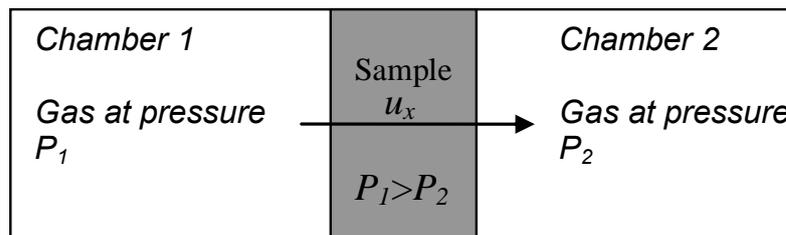
Permeability is the measure of fluid conductivity in a porous medium. The Darcy equation is used to express the flux of gas in terms of permeability and the gradient of pressure. In this equation the permeability is the coefficient of proportionality between these two entities. In one dimensional space the equation of permeation (Darcy's equation) is,

$$\psi_p = \frac{-k}{\mu} \frac{\partial p}{\partial x} \quad (1)$$

where  $\psi_p$  is the permeation gas flux (m<sup>3</sup>/m per second),  $\mu$  is the dynamic viscosity of the gas (Pa.s),  $k$  is the permeability of the medium (m<sup>2</sup>),  $p$  is the gas pressure (Pa) and  $x$  is the length (m). Note that the volumetric flux  $\psi_p$  is at pressure and temperature of gas at location  $x$ .

Measured permeability would depend on the size of the material used. This is because coal seams are highly fractured reservoirs where the length and aperture of fractures strongly depends on the dimensions of the material used. At each scale a different fracture system can be defined and therefore the permeability would be different. The fracture permeability (macro permeability) affects the initial rate of gas production or gas injection into the reservoir. However, the long term rate of gas production would depend largely on micro permeability (matrix permeability) of the medium.

For this study it is assumed that the matrix permeability is active when the size of the sample is in the order of 0.5 to 2.0 cm (the lower diameter is suitable for highly fractured coal). In Figure 2, a schematic of the CSIRO system for measurement of coal matrix permeability is shown.



**Figure 2 - Schematic of the apparatus to measure the matrix permeability**

In this system a tube is partitioned by the sample into two chambers. The two chambers are initially filled with the same gas at two different pressures. Gas flows through the sample from the high pressure chamber ( $P_1$ ) into the low pressure chamber ( $P_2$ ) until a final, almost constant, pressure ( $P_f$ ) is reached. The pressure data from the two chambers are continuously monitored using pressure transducers which communicate the data into a computer where the data are recorded onto a spreadsheet via a data logging application. The measured pressure-time data for the two chambers are used to calculate the permeability.

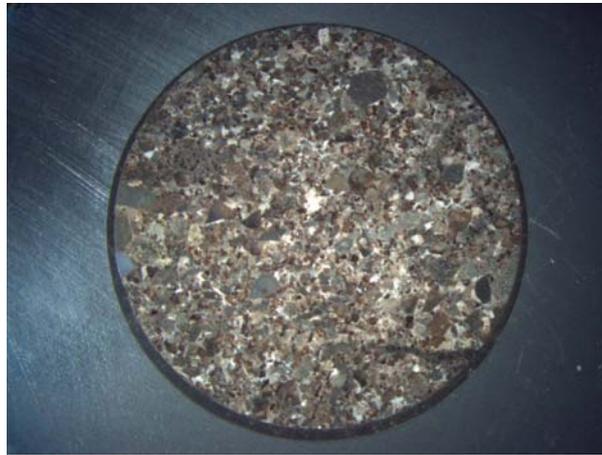
As discussed, CSG consists mainly of CH<sub>4</sub> and CO<sub>2</sub>. The rate of permeation of these gases in rock and coal are different and in this study the permeability of the rocks were measured using both gases. Variations of pore pressure, pressure gradient, and temperature can be used to evaluate the effect of different conditions on matrix permeability.

For the tests reported here the system was kept at a constant temperature (27°C). The initial pressure in the high pressure chamber,  $P_1$ , was varied from 500 to 1000 kPa while the initial pressure difference between the two chambers was about 100 kPa for all tests. The matrix permeability was determined first for helium (He) gas to determine the upper limit of gas permeability. Measurements were then taken with CH<sub>4</sub> and CO<sub>2</sub> gases respectively.

### RESULTS OF MEASUREMENT OF MICRO PERMEABILITY

Measurements were undertaken on small discs of 0.6 cm in thickness and 1.6 cm in diameter, prepared from the roof (claystone) and the floor (sandstone) core samples. In order to investigate the heterogeneity of the flow in the two main directions, the sample discs were cut parallel and perpendicular to the bedding. However, at the time of writing this paper only the results from gas flow in the direction parallel to the bedding were available and are discussed in this section of the paper.

In Figure 3, a microphotograph of the floor sample is shown. The sample diameter is about 16 mm. Under the microscope it could be seen that the mineral constituents of this sample are quartz particles surrounded by illite clay.



**Figure 3 - Photograph of sandstone sample disc (floor of coal formation) for matrix permeability and diffusivity measurement**

In Table 2, the results of 5 sets of measurements on the sandstone sample (floor rock) using helium gas (He) are presented. In this table the micro permeability is expressed both in metric units of length squared ( $m^2$ ) and in engineering units of micro darcy ( $\mu D$ ). Note that  $1 m^2 = 1.013 \times 10^{18} \mu D$ . The results show that the permeability of this rock to He decreases from 2.8 to 1.9  $\mu D$  when the gas pressure increases from 550 to 950 kPa.

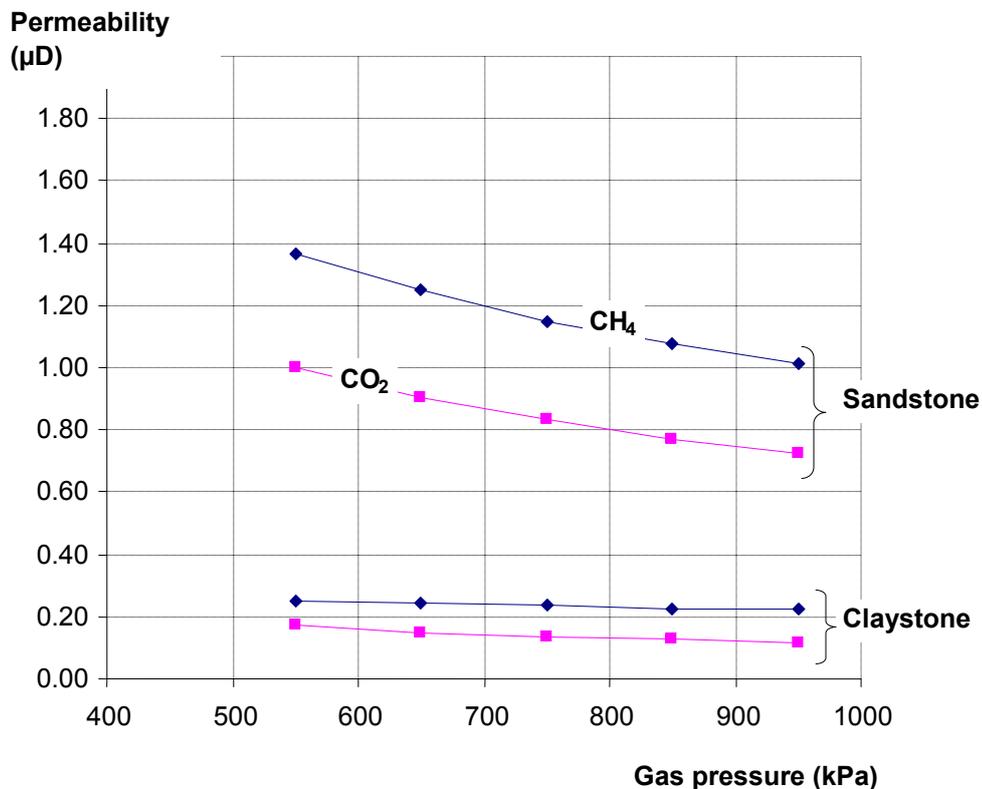
Similar sets of measurements were undertaken on this sample for CH<sub>4</sub> and CO<sub>2</sub>. Results of measurements show that sandstone micro/matrix permeability to CH<sub>4</sub> varies from 0.68 to 0.83  $\mu D$ . The matrix permeability for CO<sub>2</sub> varies from 0.40 to 0.60  $\mu D$ . For the claystone roof the results show that the matrix permeability to CH<sub>4</sub> varies from 0.23 to 0.25  $\mu D$ . The matrix permeability of claystone to CO<sub>2</sub> varies from 0.12 to 0.17  $\mu D$ .

All results are illustrated in Figure 4. For each gas pressure at least two measurements were conducted to ensure the repeatability and reproducibility of the results.

The results show that while the permeability of both floor and roof rocks reduces with gas pressure, the CH<sub>4</sub> permeability is higher than CO<sub>2</sub> for all pressures and for both rocks. Note that for both gases the micro permeability of the floor rock is 5-6 times larger than the roof rock.

**Table 2 - Measurement of micro permeability of reservoir floor rock (sandstone) to helium, diffusive flow is parallel to the bedding**

Initial and final gas pressure (kPa)			Permeability	
$p_1$	$p_2$	$p_f$	( $\mu\text{D}$ )	$\times 10^{-18}$ (m)
600	500	549.5	2.83	2.79
700	600	649.5	2.47	2.44
800	700	750.0	2.23	2.20
900	800	850.0	2.04	2.01
1 000	900	950.5	1.90	1.87



**Figure 4 - Micro permeability of the roof (claystone) and floor rock (sandstone) as a function of pore pressure**

#### MEASUREMENT OF DIFFUSIVITY

The diffusivity of a porous medium is a measure of the ease of gas propagation in the medium under the forces of a molecular concentration gradient. Gas diffuses in the direction of the smaller concentration. We assumed that the diffusion flow follows Fick's 1<sup>st</sup> law which states that the flux is proportional to the concentration gradient. The diffusivity is the coefficient of this proportionality. In one dimensional space the equation of diffusion is,

$$\psi_d = -D \frac{\partial c}{\partial x} \quad (2)$$

where  $\psi_d$  is the diffusive gas flux across solid coal,  $D$  is the gas diffusivity coefficient, expressed in terms of length squared per unit of time ( $\text{cm}^2/\text{s}$ ) and  $c$  is the gas concentration at position  $x$  in space.

In order to measure the diffusivity a system similar to the one shown in Figure 2 was used. The details of the system are presented elsewhere (Saghafi, 2001; Saghafi et al., 2007). Note that this system measures directly the diffusivity of gas in solid coal/rock. The same sample discs used for matrix/micro permeability are also used to measure the diffusivity. Because of the directional dependency of diffusivity the measurements are generally undertaken for diffusion flow parallel and perpendicular to the direction of bedding.

For the measurement of diffusivity the system can be kept at a constant temperature. For the measurements reported in this paper the temperature was kept constant at (27°C). Gas pressure was also kept constant at 101.3 kPa gauge pressure.

### RESULTS OF MEASUREMENT OF DIFFUSIVITY

In Table 3 the results of measurements of gas diffusivity for roof and floor rock samples are shown. The results are for CO<sub>2</sub> and CH<sub>4</sub> flowing in the direction parallel to bedding. The results show that the CO<sub>2</sub> diffuses faster than CH<sub>4</sub> in all cases. The ratio of the diffusivity of CO<sub>2</sub> to CH<sub>4</sub> for these measurements is about 1.17. In other words, the CO<sub>2</sub> diffusion flux is 17% higher than the CH<sub>4</sub> flux for both roof and floor rocks.

In terms of the magnitude of diffusivity for the roof and floor rocks, these measurements indicate that the rocks display similar behaviour. Though, the results show that the gas diffusivity is slightly higher for claystone sample.

**Table 3 - Results of measurement of the diffusivity of roof and floor rocks in the direction parallel to the bedding**

Rock type/Gas type	Diffusivity ( $\times 10^{-10}$ m <sup>2</sup> /s)		Diffusivity ratio
	CO <sub>2</sub>	CH <sub>4</sub>	CO <sub>2</sub> /CH <sub>4</sub>
Claystone (roof)	23.65	20.30	1.17
Sandstone (floor)	22.12	18.91	1.17

### DISCUSSION

The results so far show that permeation and diffusion take place at different speeds depending on the type of gas. In the case of permeation flow, CH<sub>4</sub> is faster than CO<sub>2</sub>. However, for diffusive flow the order is reversed, i.e. CO<sub>2</sub> diffuses faster than CH<sub>4</sub>.

Furthermore, the flow depends on the type of rock. The permeation is several times faster in sandstone compared to claystone. However, the diffusive flow shows similar behaviour for both rock types with the diffusivity slightly higher for claystone compared to sandstone.

It should be noted that although the permeability and diffusivity sub-samples were obtained from the same section of core, they were not identical and some differences may be due to the heterogeneity of the core samples.

In addition to diffusivity and permeability of non-coal rocks, the interfacial properties of gas and rocks affect the magnitude of the capillary pressure which in turn influences the intensity of gas diffusion and permeation in micro fissures of the coal and non-coal strata. The relative wetting properties of the solid (coal) to gas and water would be also studied to quantify the capillary pressures.

This study, once completed, should assist in evaluating the gas containment property of non-coal strata in a CSG reservoir for a given period of time based on the quality of the roof and floor rocks of the reservoir, and the rate of gas generation or gas injection for gas storage purposes.

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