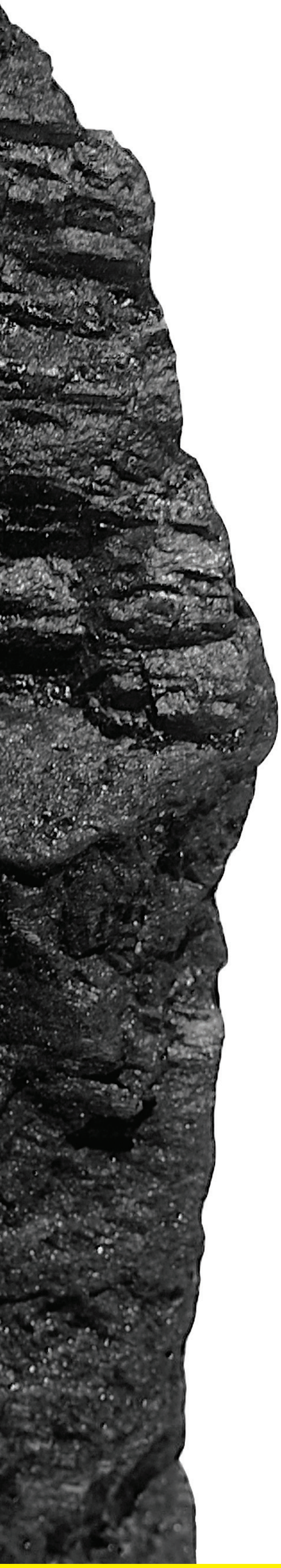
Coal Seam Reservoir Characterisation

FLUID MOVEMENT IN COAL SEAMS



Most coals exhibit some directional permeability. This usually aligns with the major direction of stress and the principal cleat. The major permeability is commonly double the minor permeability parallel to the bedding plane, and in some cases the ratio may be far higher. Permeability across the bedding planes is dependent on the continuity of cleats through out the seam. Frequently, bands of claystone, or other material slow gas migration through the seam. The permeability of coal seams also varies with production.

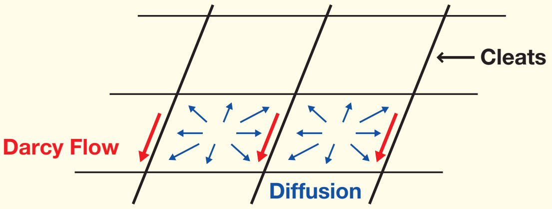
In addition to permeability, the diffusion of flow from coal blocks into cleats needs to be considered. This may be a mixture of Fickian diffusion (mass flow determined by a concentration gradient), Knudsen diffusion (flow through pores at a rate that is proportional to a pressure difference and inversely proportional to molecular weight), and small elements of Darcy flow. The latter two are practically inseparable as they are both proportional to pressure gradient.

In some coals the rate limiting step on gas production is diffusion from the solids to the cleats. This particularly applies if the cleat spacing is large and the cleats are wide open and very permeable.

It must be remembered that not all coals are initially saturated with water. In some coal seams there is free gas. These seams are the equivalent of a gas cap in a conventional petroleum reservoir.

Gas Flow in coal

The simplistic conventional concept of gas movement in coal is that the coal seams consist of solid materials which contain gas held by sorption. Coal is divided by cleats, larger joints and faults. A schematic drawing of a model containing solid coal and cleats is shown in Figure 1. This shows flow through the cleats and diffusion from the solid coal to the cleats.



Darcy Flow

$$V = -\frac{k}{\mu}\frac{dp}{dx} \quad (1)$$

Diffusion

$$F = -D\frac{dC}{dx} \quad (2)$$

Figure 1: Schematic concept of gas movement in coals.

Where V is the apparent flow velocity;

F is the Fickian flow rate (mass/(unit area . time));

D is the diffusion coefficient (length^2/time);

C is the concentration (mass/unit volume);

x is the length in the direction of flow (length).

The cleats may be saturated by water at a higher pressure than the sorption pressure of the coal. In this case all the gas is held in sorption equilibrium with a small amount in solution in the water. When the pressure is lowered in the cleats by drainage, water flows through these down a potential gradient. The potential gradient consists of pressure and gravitational terms, called Darcy flow and is described in the equation below.

$$V = -\left(\frac{k\rho}{\mu}\right)\left(\frac{d(P/\rho + gz)}{dl}\right) \tag{3}$$

Where:

V is the apparent flow velocity (flow rate/unit area = length/time);

μ is the absolute viscosity (mass/(length . time);

P is the pressure (mass/(length . time^2);

ρ is the density of the fluid (mass/length^3);

g is gravitational acceleration (length/time^2);

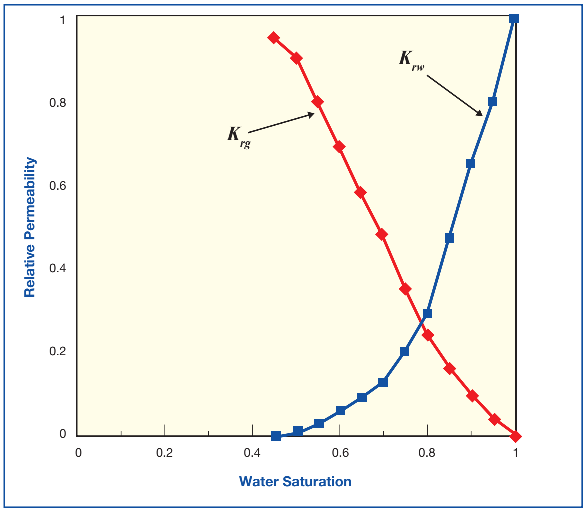
z is the elevation (length);

l is the length in the direction of flow (length).

Permeability

Once the fluid pressure in coal drops to below the sorption pressure, gas bubbles begin to release from the coal. These bubbles displace water from the cleat space. In doing so, the effective permeability of the coal to water and gas, changes with gas impeding the passage of water and vice versa. This type of behaviour may be described by relative permeability curves, such as in Figure 2 - one applying to gas (K_{rg}) and one applying to water (K_{rw}). The effective permeability for each phase (water and gas) is arrived at by multiplying the absolute permeability by the relative permeability.

Figure 2: An example of relative permeability curves.



Effective Stress

The relative permeability of coal varies with water saturation and the absolute permeability varies with effective stress. Effective stress is the total stress in any direction minus a fraction of the fluid pressure. This fraction depends on how continuous the fluid filled cleats are.

In a coal seam without fluid pressure, the stress is carried across any cleat or fracture directly. Fluid under pressure in the cleat network will lead to that fluid taking some of the load. The effective stress equation is therefore:

$$\textit{Effective Stress} = \textit{Total Stress} - c \times \textit{Fluid pressure} \tag{4}$$

Where c depends on cleat continuity and generally in most seams approaches unity as continuity increases.

Coal is a soft rock, usually containing a cleat network. The coal on each side of a cleat does not meet perfectly and as the effective stress rises the cleats close up reducing the permeability. Generally the relationship between permeability and stress is of the form:

$$\log k = \log k_0 - 1/b \times (\textit{effective stress}) \tag{5}$$

Where:

k is the absolute permeability in a direction within the coal;

k_0 is the permeability at zero effective stress;

b is the stress-perm coefficient.

The stress-perm coefficient (b) is the change in effective stress required to produce an order of magnitude change in permeability.

In a soft coal b may be of the order of 3MPa while in harder coals it may be much higher.

If a soft coal changes its fluid pressure by 3MPa during drainage, then assuming the value of the stress-perm coefficient (b) is 3MPa in the soft coal, this pressure change and the corresponding increase in effective stress may lead to an order of magnitude of permeability reduction.

Shrinkage and Stress

Coal is unlike other rocks in that it shrinks as it gives up gas or water. This behaviour can be physically observed by measuring coal with a precise device, such as a micrometer or strain gauge system, while changing the gas pressure. An example of the horizontal strain changes measured with different sorption pressures is shown in Figure 3. The x-axis shows the sorption pressure while the y-axis displays the strain. This case shows a change of 1500 and 1800 microstrain over a sorption pressure change of 3MPa.

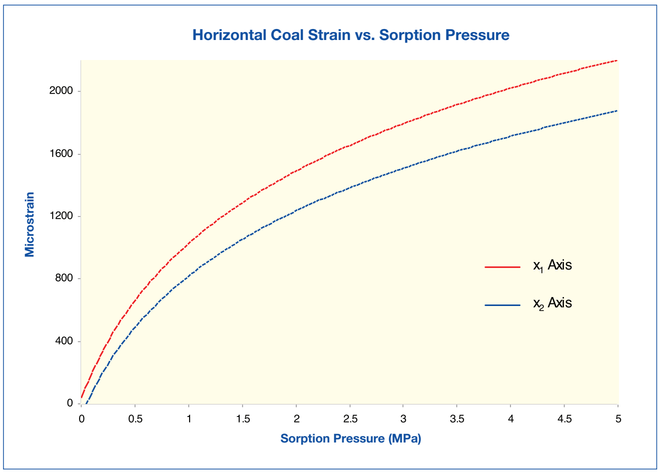


Figure 3: Example of changes in horizontal strain (2 axes) with sorption pressure.

Shrinkage of the coal leads to a lowering of horizontal stress levels. In an extensive horizontal degassing situation the total vertical stress is maintained by the gravitational load of the strata above the seam. The vertical effective stress, however, increases because the in-seam fluid pressure is decreasing. The effective horizontal stress is, however, a different situation. The roof and floor strata tend to maintain a relatively even horizontal strain. If fluid is withdrawn from the coal there is a transfer of stress from the fluid to the coal.

The horizontal stress increase in the coal due to the change in vertical stress is:

$$\Delta\sigma'_{h/sw} = \Delta\sigma'_{v}\left(\frac{v}{1-v}\right) \tag{6}$$

Where:

$\Delta\sigma'_{h/sw}$	is the change in effective horizontal self weight stress;
$\Delta\sigma'_{v}$	is the change in effective vertical stress;
v	is Poisson's ratio.

The horizontal stress changes brought about by shrinkage are:

$$\Delta\sigma_{sh/1} = \frac{-E}{1-v^2}\left(\Delta\varepsilon_{sh/1} + v\Delta\varepsilon_{sh/2}\right) \tag{7}$$

$$\Delta\sigma_{sh/2} = \frac{-E}{1-v^2}\left(\Delta\varepsilon_{sh/2} + v\Delta\varepsilon_{sh/1}\right) \tag{8}$$

Therefore the net effective changes in horizontal stress caused by drainage are:

$$\Delta\sigma'_{h/1} = \Delta P(1+\left(\frac{v}{1-v}\right)) - \frac{E}{1-v^2}\left(\Delta\varepsilon_{sh/1} + v\Delta\varepsilon_{sh/2}\right) \tag{9}$$

$$\Delta\sigma'_{h/2} = \Delta P(1+\left(\frac{v}{1-v}\right)) - \frac{E}{1-v^2}\left(\Delta\varepsilon_{sh/2} + v\Delta\varepsilon_{sh/1}\right) \tag{10}$$

Where:

$\Delta\sigma'_{h/1}$	is the effective stress change in the horizontal plane in direction 1;
$\Delta\sigma'_{h/2}$	is the effective stress change in the horizontal plane in direction 2;
ΔP	is the change in fluid pressure;
$\Delta\varepsilon_{sh/1}$	is the strain due to shrinkage in the horizontal plane in direction 1;
$\Delta\varepsilon_{sh/2}$	is the strain due to shrinkage in the horizontal plane in direction 2;
v	is Poisson's ratio;
E	is Young's modulus.

Without shrinkage effects, a reduction in fluid pressure will bring about an increase in effective horizontal stress (equation 6). If shrinkage effects occur, then equations 9 and 10 describe the combined effect. In some cases horizontal effective stress will increase while in others it will decrease. The effects of stress changes on permeability are given by equation 5. Where shrinkage dominates and causes an effective stress reduction, the permeability will decrease and vice versa.

If the horizontal effective stress drops to zero, then the cleats will open up with further shrinkage. Theoretically, the permeability of a group of open parallel cleats is given by equation 11. This equation is useful in determining the importance of cleat spacing and effective cleat width.

$$k = A\left(\frac{a^3}{12}\right) \tag{11}$$

Where:

k is permeability;

A is the cleat density per unit length;

a is the cleat width.

A Practical Example

In a practical situation, fluid pressure will be lowered by drainage. With this drop in fluid pressure the effective stress will increase, leading to a drop in permeability. As shrinkage takes effect this drop in permeability will either slow or possibly reverse. In an extreme case this reversal is of such a size that zero horizontal stress will exist in the coal and the cleats open up with an ensuing significant increase in permeability.

Figure 4 approximates the situation at Leichhardt Colliery Queensland. It shows where the permeability began at 0.1 millidarcies with a 4.2MPa seam pressure. Initial water drainage takes place to 3.8MPa when the sorption pressure is reached and gas is emitted from the coal.

In this pressure range the permeability declines due to an increase in effective stress. This trend would continue (blue line) except that in the real case shrinkage occurred (red line) causing a reduction in effective stress and an increase in permeability to 1 millidarcy at 2.7MPa gas pressure. At this pressure zero effective stress exists across the cleats. As gas pressure declines futher the permeability increases dramatically to 500 millidarcies at 0.5MPa pressure. This case is extreme but demonstrates the importance of shrinkage.

Figure 4: Changes to permeability due to effective stress and shrinkage. Taken from Gray (1987).