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Permeability Measurement in Coals and the Importance of Stress Path

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Abstract

The permeability of coals varies widely both in location and the production of water and gas. Knowing what the permeabilities are and how they will vary is very important to the extraction of gas from coal seams for commercial purposes or making mining possible.

Coal Permeability

Whilst it is useful to look at coal core for the purpose gaining some idea as to what the cleat structure is and whether those cleats are filled with mineralisation, it is not possible to reliably measure coal permeability from that core. The reason for this is that the core generally does not contain a statistically representative sample of the cleats and joints that contribute to permeability within a coal seam in order for a meaningful measurement to be made on a readily obtainable core sample. This conclusion applies to relative permeability as well as to absolute permeability.

Because of the inadequacy of core permeability testing it is necessary to conduct field measurements of permeability. Field measurements may be divided into those that are undertaken prior to production and those obtained during production. Ideally, the pre-production measurements can be used to model the entire production life of the reservoir. However, to do so a somewhat more sophisticated process than a conventionally analysed drill stem test is required, though conventional tests can be used to yield a great deal of information. What is really needed are measurements that define directional permeability and enable an estimation of the change in permeability with fluid production. Stress and structure are key to this.

Coals have been tested that have in seam directional permeability ratios, which are so high that they have essentially immeasurably low permeability in one direction whilst having a moderate permeability in the orthogonal direction. Others have been found to exhibit no directional permeability. The permeabilities in different directions may be due to completely different structures such as cleats compared to widely spaced joints. Coals generally exhibit a strong relation between effective stress and permeability. This has been shown to be the case with direct core measurement and through field experience. Thus determining the relation between effective stress and permeability is very important.

Any single field test for permeability is likely to yield only a local snapshot of permeability at the time of that measurement. To be able to determine permeability changes something more needs to be done. This comprises the determination of the permeability-effective stress relation and that of the changes in effective stress.

Practical Field Measurements of Permeability In Coals

All permeability measurements involve the measurement of changing pressure associated with flow, though the flow may be zero for part of a test. There are always complications in the analysis of a permeability test associated with the presence of a well bore and drilling fluids. For this reason, tests that minimise these complications are likely to yield the most reliable results. Thus, a production test where only reservoir fluid is produced is likely to be more successful than one where a foreign fluid is being injected. So too is one where the flow during the critical measurement period is zero, such as in a drill stem test, so as to minimise well bore loss behaviour.

If a test involves only a single fluid then it is likely to be much simpler to deal with as this removes the complications of mixed phase flow and relative permeability effects. Where the permeability of the reservoir varies with effective stress, and therefore fluid pressure, it becomes essentially impossible to separate the effects of relative permeability from effective stress dependent permeability in a well test. Stress dependent effects may be minimised by reducing the pressure change brought about during testing.

The single most useful permeability test that can be undertaken in a coal is a drill stem test that does not drop the pressure significantly, thus avoiding desorption of gas, and the generation of a two-phase regime. Such a test does not however provide any information on directional permeability, nor on the stress dependent permeability.

If testing can be undertaken within a water saturated coal then the high stiffness of the fluid means that it is possible to undertake transient testing which encompasses a large area of the coal seam within a comparatively small time, provided that the coal has adequate permeability. It also permits the use of various forms of interference testing. These are essentially tests that involve measuring the pressure transient response of the reservoir at a location away from the test well.

The benefit of measuring a flow from a test well, but also measuring the pressure transient at a location that is remote from it, is three fold. Firstly, it isolates the test from near well bore damage, and secondly it avoids problems associated with large pressure variations changing permeability around the well bore. Thirdly, provided there are enough observation bores fitted with pressure sensors, it enables directional permeability to be determined.

While it is theoretically possible to determine directional permeability using a test well and three observation wells, this approach does not enable the heterogeneity of the seam to be separated from the anisotropy. The heterogeneity of the coal seam may frequently be much more important than anisotropy, or from an alternative viewpoint, the anisotropy is so irregular that it is impossible to separate it from the heterogeneity. Such cases occur in areas of structural complexity.

To overcome these issues the use of pulsed DST testing may be particularly useful. In this case, a DST test is performed in one seam location to reveal the mean permeability. A pressure transducer is then installed in it. Another hole is then drilled and another DST test is performed yielding another mean permeability and a directional permeability. This hole then has a pressure transducer installed in it and a third well is drilled and a DST performed yielding yet another mean permeability and two directional permeability values. This is an adequate number of measurements (3) to determine the directional permeability tensor in its own right as well at three discrete measurements of mean permeability.

If the variation in the measurements of mean permeability is of similar value to the difference between the apparent major and minor values of the permeability tensor, then the determination of directionality is meaningless.

When the determination of permeability is conducted below the sorption pressure, with free gas being present, the situation becomes much more complex. Firstly, all testing is slowed because the compressibility of the gas is much higher than that of water. If the testing is slowed too much then the effects of desorption through a process of diffusion need to be accounted for. This adds an entirely separate layer of uncertainty. Finally, unless the coal seam is initially dry, there are the problems of two-phase flow to take into account.

In these multiphase situations, attempts at the determination of permeability become one where back analysis has to be performed using a simulator. This is a complex operation where unique parameters are hard to determine. Several approximate scenarios of groups of permeability related variables including those related to effective stress through fluid pressure and water saturation through the relative permeability curve may be derived. To make matters more difficult the modeller is nearly always presented with initial gas contents, sorption isotherms and production flow data on which to base such a back analysis. Without the benefit of in-seam pressure transducers, this task becomes extremely unreliable. Invariably the model derived must then be used for future prediction of the production characteristic of the seam. This nightmare is reality for most reservoirs and hence reservoir engineers resort to such black magic as decline curves to predict long-term behaviour.

The Structural and Stress Path Approach to Permeability Variation

What is needed is an alternative approach to determine how a coal seam reservoir will perform. This approach should take full account of the structure within the seam and the stresses acting upon it. Finally, it should take into account the effect of changing stress on the structure and how this will affect permeability.

Generally, we think that in cleated stressed coals the permeability is adequately described by equation (1).

$$\log k = \log k_o - \frac{\Delta\sigma_{eff}}{b} \qquad (1)$$

where k is the absolute permeability
k_o is the permeability at the initial effective stress state
$\Delta\sigma_{eff}$ is the change in the effective permeability
b is the change in effective stress required to bring about one order of magnitude permeability variation

The effective stress may only be thought to be that acting normal to a cleat or fracture group. Making the assumption that Biot’s coefficient in a cleated coal is close to unity and therefore that the effective stress is essentially the total normal stress minus the fluid pressure several estimates for b lying from about 0.7 to 5 MPa have been derived. These numbers come from back analysis of production tests with shut in periods and from the analysis of DST tests that have only produced water.

As the fluid pressure change alone in seam may be similar to or several times b the permeability could be expected to decrease by one or more orders of magnitude. However, the effects of shrinkage of the coal as it gives up gas may change this. This shrinkage tends to lead to a reduction in effective stress. This effect is more pronounced in stiffer coals.

The question is then how will the permeability change with production? This is critically dependent upon the stress path that the coal follows during drainage. Figure 1 shows an example of a horizontal stress path derived for a particular coal seam where the fluid pressure starts at 5 MPa. At three MPa desorption occurs and shrinkage dominates over fluid pressure reductions to the state where no lateral stress exists in the seam at about one MPa. Unfortunately in many coals this stress reduction is not the case and the effective stress increases leading to a drop in permeability.

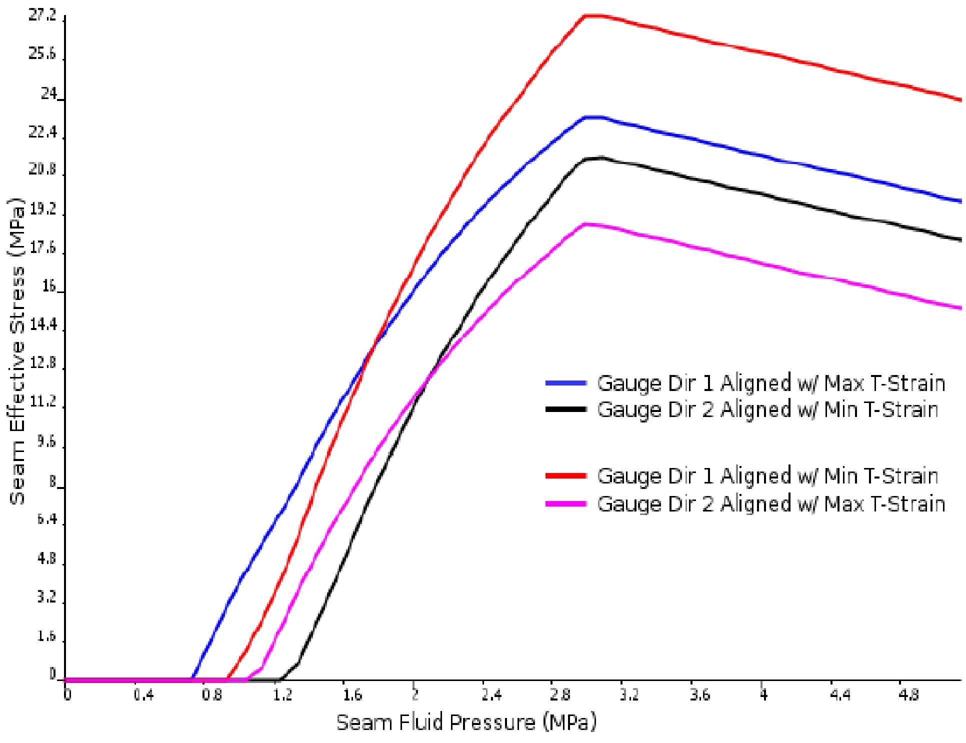

Figure 1. An example of a horizontal stress path.