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Laboratory characterisation of coal matrix shrinkage, cleat compressibility and the geomechanical properties determining reservoir permeability

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ABSTRACT

This paper presents the results of a laboratory program of work to measure the coal properties required to apply models for the behaviour of the absolute reservoir permeability during gas production. These measurements were made on core samples from the Bowen Basin of Australia, an important area for coal seam methane production, and involved applying an integrated testing methodology. During the testing the pore pressure was increased in a stepwise fashion with gas adsorption equilibration allowed at each pressure step. The gas content of the intact sample was estimated from the gas taken up during equilibration and the sample swelling in response to adsorption measured. After adsorption had equilibrated, the geomechanical properties were determined through axial loading and measurement of the deformation and the permeability measured with respect to confining pressure. These permeability measurements were then used to estimate the cleat compressibility by fitting the Seidle model to the observations. The results from five coal samples are presented. A method is presented for the calculation of the cleat porosity, a difficult property to determine experimentally as it represents the proportion of the porosity involved in Darcy flow. Thus, the presented method uses a property determined from flow measurements; the cleat compressibility. The measured properties are used in the Shi–Durucan model to predict permeability behaviour with pressure drawdown. The results are compared to the field based estimates from the analysis of Mazumder et al. (2012).

1. Introduction

As with many reservoirs, permeability usually plays a central role in determining coal seam methane production. Coals are viewed as naturally fractured reservoirs with a matrix that is usually assumed to have a negligible permeability in comparison to the fracture system. These fractures in coal are known as cleats with the cleat aperture sensitive to the effective stress; increased effective stress acting to decrease the cleat aperture and thus permeability. A unique aspect of coal is that adsorption is the dominant gas storage mechanism with reservoirs typically water saturated prior to production and therefore without free gas. As gas desorbs the coal matrix shrinks, and swells with adsorption (in this paper this shrinkage or swelling will be referred to as sorption strain). Drawing down the reservoir pressure leads to gas desorption and matrix shrinkage tending to increase cleat apertures and permeability. During production, the counteracting processes of matrix shrinkage and effective stress operate on cleat apertures meaning that coal reservoir permeability varies with time.

Modelling coal permeability during production is an active area of research with numerous models being presented. Gray [11] model for coal permeability couples the effects of the matrix shrinkage and pore pressure changes and assumes uniaxial strain and constant vertical stress in order to simplify the geomechanical problem and derive an effective stress based approach for the variation in permeability. Palmer and Mansoori [20,21] also used uniaxial strain and constant vertical stress to derive a porosity based formulation. While Shi and Durucan [30,31] also used these assumptions with the equations of linear elasticity and the Seidle et al. [28,29] model for coal permeability with effective stress.

These models involve a range of properties such as the geomechanical properties, the sorption strain and permeability properties such as the cleat compressibility and absolute permeability. Obtaining meaningful estimates of these properties is important to the accurate prediction of gas production in reservoir

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simulation. Pan et al. [24] presented a method for laboratory characterisation of coal permeability behaviour during gas production. In Pan et al.'s paper, an integrated laboratory characterisation using coal core samples was used to estimate the various properties to apply the Palmer–Mansoori and Shi–Durucan coal permeability models. Since this technique is based on coal core there will be differences due to the scale of the measurements relative to the scale of the reservoir processes. In particular, coal permeability is sensitive to measurement scale and is best determined by well testing. In addition, the geomechanical properties are usually scale dependent [19]. However, sorption strain and cleat compressibility are very difficult to determine without extensive production data but even then differentiating the effect of these properties from other processes can be challenging. The Pan et al. [24] methodology provides measurements that could be used as starting points for further refinement in history matching.

Espinoza et al. [9] present a detailed laboratory characterisation study on coal core where a broad range of adsorption, sorption strain, geomechanical properties and the response of permeability were measured. As part of this study, a poromechanical model for dual-porosity in transverse isotropic fractured coal was presented and parameterised using observations from constant stress experiments. The model was then tested against observations from constant volume experiments.

An alternative field based procedure is that used by Mazumder et al. [18] where the coal permeability model properties were estimated by using multiphase pressure build-up analysis from a history of well shut-in data.

A common assumption in the application of Shi–Durucan and Palmer–Mansoori models is that the coal properties are constant with respect to pressure. However, this is a simplifying assumption and the physical properties may change with pressure and stress. For example, the cleat aperture decreases in response to increased effective stress which could lead to increased contact between the faces of the cleats and a decrease in the cleat compressibility. Shi and Durucan [32] presented a modified form of their original model where the cleat compressibility varied with effective horizontal stress.

Pan et al. [24] estimated cleat compressibility using permeability measurements over a range of pressures and found that it was not constant with respect to pressure. Pan et al. went on to compare the permeability calculated using the measured variation with that assuming the cleat compressibility was constant. It was found that there were significant differences between the two sets of results. Robertson and Christiansen [27] also used laboratory measurements of permeability to estimate the cleat compressibility and found it was not constant. Mazumder and Wolf [16] determined the cleat compressibility through history matching of gas displacement experiments on coal core. Palmer [22] presented evidence from several sources that showed that the cleat compressibility may not be constant. In Mazumder et al. [18] analysis of well shut-in observations, the Shi and Durucan [30] model for cleat compressibility with effective horizontal stress was used to describe its variation.

This paper presents the results of a laboratory characterisation program using coal core to estimate the properties required to apply the Shi–Durucan and Palmer–Mansoori models for coal permeability. The results of this characterisation program are compared with field based analysis of Mazumder et al. [18]. In the first section of the paper, measurements of a range of general physical properties, including organic petrology, are presented to provide an insight into the coal being used in this work.

2. Characterisation of coal physical properties

The coal cores used in this program of work came from the coal seams of the northern Bowen Basin, Australia. Each core was recovered from a different well and seam and so a broad range of coals are covered in this study. Table 1 presents a summary of the measurements performed for each sample and the depth from which the sample was recovered. Samples A1 and A5 were characterised early in the experimental program when the focus was characterisation of CH_4 related properties and so therefore do not have the broad range of measurements conducted for the other samples.

A summary of the coal sample's physical properties are presented in Table 2. These measurements were made on the offcuts from the core sample preparation. The helium solid density was measured using a Instruquest HumiPyc gas pycnometer. After crushing, mixing and using a sample splitter to obtain a representative sample, approximately 3 g of coal was used in each measurement. The instrument used for surface area analysis was an ASAP 2420 Accelerated Surface Area and Porosimetry System. Before this

Table 1
The depth from which the sample was recovered and a summary of the measurements performed.

Sample ID	Depth (m)	Physical properties	Sorption strain	Geomechanical properties	Solid modulus	Adsorption isotherm	Cleat compressibility
S1	451	Yes	N_2, CH_4, CO_2	Yes	Yes	N_2, CH_4, CO_2	N_2, CH_4, CO_2
S2	593	Yes	N_2, CH_4, CO_2	Yes	Yes	N_2, CH_4, CO_2	He, N_2, CH_4, CO_2
S3	214	Yes	N_2, CH_4, CO_2	Yes	Yes	N_2, CH_4, CO_2	He, N_2, CH_4, CO_2
S4	<100	Yes	N_2, CH_4, CO_2	Yes	Yes	N_2, CH_4, CO_2	He, N_2, CH_4, CO_2
A1	263		CH_4	CH_4	Yes	CH_4	CH_4
A4	721	Yes	N_2, CH_4, CO_2	CH_4, CO_2	No	N_2, CH_4, CO_2	He, N_2, CH_4, CO_2
A5	136	Yes	CH_4	CH_4	Yes	CH_4	CH_4

Table 2
Summary of the measurements of the coal sample's physical properties.

Sample name	N_2 BET surface area (m^2/g)	N_2 porosity (%)	CO_2 BET surface area (m^2/g)	CO_2 porosity (%)	Solid density (g/cm^3)	Bulk density (g/cm^3)	Vitrinite reflectance (%)	Mineral free maceral composition (%)			Total organic matter (%)
								Liptinite	Vitrinite	Inertinite	
S1	3.3	0.33	92	1.07	1.68	1.50	1.85	0	58.1	41.9	90.9
S2	2.1	0.23	102	1.04	[a]	1.54	1.42	0	83.9	16.1	94.2
S3	1.45	0.17	96	1.55	1.50	1.29	1.49	0	70.1	29.9	80.6
S4	3.3	0.60	85	1.54	1.81	1.30	0.97	1.9	45	53.1	87.8
A4	1.07	0.17	88	1.57	1.50	1.21	1.31	0	72.9	27.1	90.9
A5	2.78	0.34	85	1.01	1.62	1.49	1.27	0	68.5	31.5	94.2

[a] Insufficient sample for this measurement.