International Journal of Coal Geology 84 (2010) 103–114

Contents lists available at ScienceDirect

International Journal of Coal Geology

journal homepage: www.elsevier.com/locate/ijcoalgeo

# An analytical coal permeability model for tri-axial strain and stress conditions

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A R T I C L E I N F O

*Article history:*
Received 12 February 2010
Received in revised form 20 August 2010
Accepted 20 August 2010
Available online 19 September 2010

*Keywords:*
Coal
Coalbed methane
Permeability
Triaxial testing

A B S T R A C T

Coal permeability is sensitive to the effective stress and is therefore coupled to the geomechanical behaviour of the seam during gas migration. As coal shrinks with gas desorption and swells with adsorption, understanding this coupling to geomechanical behaviour is central to interpreting coal permeability. Existing coal permeability models, such as those proposed by Shi and Durucan (2004) and Palmer and Mansoori (1996), simplify the geomechanical processes by assuming uni-axial strain and constant vertical stress. However it is difficult to replicate these conditions in laboratory tri-axial permeability testing and during laboratory core flooding tests for enhanced coal bed methane. Often laboratory tests involve a hydrostatic stress state where the pressure in the confining fluid within the tri-axial cell is uniformly applied to the sample exterior. In this experimental arrangement the sample is allowed to undergo tri-axial strain. This paper presents two new analytical permeability model representations, derived from the general linear poroelastic constitutive law, that include the effects of tri-axial strain and stress for coal undergoing gas adsorption induced swelling. A novel approach is presented to the representation of the effect of coal sorption strain on cleat porosity and thus permeability. This involves distinguishing between the sorption strain of the coal matrix, the pores (or cleats) and the bulk coal. The developed model representations are applied to the results from a series of laboratory tests and it is shown that the models can predict the laboratory permeability data. As part of this characterisation the various sorption strains are identified and it is shown that the pore strain is significantly larger than (approximately 50 times) the bulk sorption strain. The models also provide further insight into how coal permeability varies with coal shrinkage and swelling and how the permeability rebound pressure depends upon the effective stress applied.

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## 1. Introduction

The permeability of coal is a key attribute in determining coal seam methane production and $CO_2$ storage in coal seam reservoirs. In coal the permeability is often determined by regular sets of fractures called cleats, with the aperture of the cleats being a key property in the magnitude of the permeability. This cleat aperture is sensitive to the effective stress, with increased effective stress acting to decrease the cleat aperture and thus permeability. Gas in coal is largely stored by adsorption which introduces another complication in the understanding of coal permeability behaviour; as gas desorbs from coal the coal matrix shrinks, with gas adsorption the matrix swells. In this paper this shrinkage or swelling will be referred to as sorption strain. Thus there are two competing effects on coal permeability; lowering the pore pressure (such as during primary production) acts to increase the effective stress and thus reduces the permeability due to cleat compression. However the drawdown also results in desorption of methane leading to matrix shrinkage and increased coal cleat apertures and thus permeability. Conversely, raising the pore pressure and gas content (such as during $CO_2$ storage to enhance coal bed methane recovery) will reverse the processes described in the preceding sentence. Thus, the permeability of coal is not a monotonically increasing or decreasing function of reservoir pressure. Instead, it may have a minimum, corresponding to a specific pressure, called the permeability rebound pressure.

Gray (1987) presented a coal permeability model which represents the effects of the matrix shrinkage and pore pressure changes on coal permeability. Various other models have been presented, including Harpalani and Zhao (1989), Sawyer et al. (1990), Seidle et al. (1992), Seidle and Huitt (1995), Palmer and Mansoori (1998), Gilman and Beckie (2000), Shi and Durucan (2004, 2005), Palmer (2009), *etc.*, where both the shrinkage and pore pressure effects are included. Recently, Liu and Rutgvist (2009) have developed a new coal permeability model in the form of the combination of cubic and exponential representations. Liu et al. (2010) presented a coal permeability model based on a different interpretation of the coal structure to those dervied from the Seidle et al. (1992) bundled match-stick concept. Among these models, the Palmer–Mansoori (P–M) model (1998) and the Shi–Durucan (S–D) model (2004, 2005) are currently two popular choices used in reservoir simulation of gas migration.

Two assumptions are applied with the above-mentioned models in order to simplify their derivation and provide a concise equation convenient for representing the permeability behaviour; these are *uni-*

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doi:10.1016/j.coal.2010.08.011

*axial strain* and constant *overburden* or *confining stress*. However these conditions may not always be satisfied within the reservoir as discussed by Durucan and Edwards (1986) and more recently investigated using coupled modelling by Connell and Detournay (2009) and Connell (2009). An important example regarding this issue is in relation to laboratory testing of core samples in tri-axial cells. This testing is used for the characterisation of permeability and in core flooding. For these tests (details of which will be further illustrated below) the coal sample is in a hydrostatic stress state and allowed to undergo tri-axial strain (for example, see Durucan and Edwards, 1986). However the existing coal reservoir permeability models are based on assuming uni-axial strain and constant vertical stress, conditions that are more difficult to replicate in the laboratory. Pan et al. (2010) presented a method for laboratory characterisation of coal permeability under tri-axial condition. Measurements of geomechanical properties, sorption strain and cleat compressibility with respect to confining pressure or pore pressure variation are also presented. Although these measurements can be applied to permeability models developed assuming uni-axial conditions, these models cannot represent the permeability behaviour with respect to confining and pore pressure changes under hydrostatic, tri-axial conditions. Thus, in order to more readily represent the routine conditions for laboratory testing, a new model is needed as these strain and stress assumptions can have a significant impact on the permeability.

This current paper presents two new analytical model representations; one is of an exponential form and the other a cubic form, in a manner consistent with Shi–Durucan and Palmer–Mansoori coal permeability models. Both models accommodate the two effects discussed above of sensitivity to effective stress and sorption strain. In the derivation of the models it is found that sorption strain needs to be partitioned into bulk, pore and matrix strains in contrast to existing approaches. Several different forms of the permeability models are derived for the distinct geometric and mechanical arrangements that can be encountered with laboratory testing. The approach employed could be extended to more general cases including possible field applications. A discussion of the two new models is presented, and they are then applied to a set of laboratory experimental data where the core permeability had been measured and the various geomechanical and permeability properties determined through a series of independent measurements.

## 2. Model formulation

### 2.1. Two general model representations

In this section the theoretical basis for the models developed in this paper is presented. In the next section the model derivations are presented for laboratory testing with tri-axial deformation and cylindrical geometry of core samples.

The volumetric balance between the volume of bulk rock ($V_b$), the grain or *matrix* volume ($V_m$), and the pore (or the cleat for coal) volume ($V_p$), is $V_b = V_p + V_m$. Since coal has a dual porosity structure there are two porosity systems involved. It is commonly assumed that it is the macro-porosity, or cleat porosity, that determines the permeability and thus Darcy flow and that the micro-porosity typically does not play a significant role in this process. Thus, in this paper, given the focus on permeability the pore volume that is referred to is the cleat pore volume and to be consistent with the general literature the subscript p is used for quantities associated with this. In addition the pressure of the cleat system is referred to as the pore pressure in order to be consistent with the general literature. The porosity of the rock ($\phi$) is defined as $\phi = V_p / V_b$. In a similar fashion to Cui and Bustin (2005) by differentiating $V_b$ and $\phi$, respectively, one obtains

$$\frac{d\phi}{\phi} = d\varepsilon_b - d\varepsilon_p \tag{1}$$

and

$$\frac{d\phi}{1-\phi} = d\varepsilon_m - d\varepsilon_b. \tag{2}$$

The permeability ($k$) of a coal can be related to its cleat porosity through (*e.g.*, Seidle et al., 1992; Palmer and Mansoori, 1998; Shi and Durucan, 2004; Cui and Bustin, 2005, *etc.*)

$$k = k_0 \left(\frac{\phi}{\phi_0}\right)^3 \tag{3}$$

In Eqs. (1) and (2), $d\varepsilon_p = -dV_p/V_p$ is the (differential) pore strain, $d\varepsilon_b = -dV_b/V_b$ the (differential) bulk rock strain, and $d\varepsilon_m = -dV_m/V_m$ the (differential) grain (matrix) strain; $k_0$ and $\phi_0$ are the permeability and cleat porosity of the coal at a reference state, respectively.

Eqs. (1) and (2) are exact and provide a basis for considering the relationship between cleat porosity and strain in coal reservoirs. When combined with the well supported cubic relationship between permeability and cleat porosity defined by Eq. (3), a relationship between strain and permeability can be derived. In this paper two model forms are developed for the behaviour of permeability during changes in pressure and gas content in coal reservoirs; in the first section below an exponential equation is derived, of a similar form to the Shi–Durucan coal permeability model. In the second section below, a cubic equation is derived, which is the form of the Palmer–Mansoori equation. In sections to follow the derived equations are then compared to these two widely adopted coal permeability models.

#### 2.1.1. The exponential form

Integration of Eq. (1) immediately gives

$$\frac{\phi}{\phi_0} = \exp\left[-\left(\int_{\varepsilon_p^0}^{\varepsilon_p} d\bar{\varepsilon}_p - \int_{\varepsilon_b^0}^{\varepsilon_b} d\bar{\varepsilon}_b\right)\right], \tag{4}$$

where $\varepsilon_p^0$ and $\varepsilon_b^0$ denote the corresponding counterparts of $\varepsilon_p$ and $\varepsilon_b$ at a reference state, respectively.

An important effect in coal is the sorption strain where the coal matrix swells with gas adsorption and shrinks with desorption. This can be included into the bulk rock strain $\varepsilon_b$ and the pore strain $\varepsilon_p$ by considering the total derivative. In fact, the total changes of bulk rock volume $dV_b$ and that of pore volume $dV_p$ can, based on the volume balance, be decomposed into two parts; one that is caused by the mechanistic tractions (denoted by $dV_b^{(M)}$and $dV_p^{(M)}$, respectively) and the other by the gas sorption (denoted by $dV_b^{(S)}$and $dV_p^{(S)}$, respectively). That is, $dV_b = dV_b^{(M)} + dV_b^{(S)}$ and $dV_p = dV_p^{(M)} + dV_p^{(S)}$. Accordingly, $\varepsilon_b$ and $\varepsilon_p$ can be written as

$$d\varepsilon_b = d\varepsilon_b^{(M)} + d\varepsilon_b^{(S)} \quad and \quad d\varepsilon_p = d\varepsilon_p^{(M)} + d\varepsilon_p^{(S)}, \tag{5}$$

where $\varepsilon_b^{(M)}$ and $\varepsilon_p^{(M)}$ denote the mechanistic strains of rock and pore, respectively; $\varepsilon_b^{(S)}$ and $\varepsilon_p^{(S)}$ are the strains of rock and pores introduced by matrix swelling due to gas sorption there, namely, both of them are functions of the pore pressure ($p_p$).

The bulk matrix mechanistic strain $\varepsilon_b^{(M)}$ in Eq. (5), using the approach of Zimmerman et al. (1986) and Jaeger et al. (2007), can be expressed by

$$d\varepsilon_b^{(M)} = C_{bc}^{(M)} dp_c - C_{bp}^{(M)} dp_p, \tag{6}$$

where,$C_{bc}^{(M)} = -(\partial V_b/\partial p_c)_{\{p_p, \varepsilon_b^{(S)}\}}/V_b$ and $C_{bp}^{[M]} = -(\partial V_b/\partial p_p)_{\{p_c, \varepsilon_b^{(S)}\}}/V_b$ are compressibilities similar to those defined by Zimmerman et al. (1986); the difference is only that here $V_b$ is the current bulk volume of the rock rather than its counterpart ($V_b^0$). $C_{bc}^{(M)}$ and $C_{bp}^{(M)}$ can be related

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