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Analytical models for coal permeability changes during coalbed methane recovery: Model comparison and performance evaluation

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ABSTRACT

An in depth comparison of four permeability models, Palmer and Mansoori (P&M) model, Shi and Durucan (S&D) model, Cui and Bustin (C&B) model and the improved P&M model, developed under uniaxial strain conditions prevailing in coalbed reservoirs, was carried out focusing on the relative influence of the matrix shrinkage term over the compaction term in each model. The ratio of the coefficients of the two terms is shown to have a direct impact on the magnitude of permeability rebound pressure, which is a key parameter controlling the modelled response of coalbed permeability to reservoir drawdown. P&M model and C&B model are found to yield essentially the same permeability rebound pressure, which is significantly lower than that given by S&D model. Cleat porosity change in P&M model has been shown to be controlled by the effective mean stress, indicating that it is essentially a mean stress model (as C&B model). With the introduction of an empirical parameter g (<0.3) in the model equations to suppress the pressure-dependent effect on permeability, the improved P&M model gives rise to a permeability rebound pressure much larger than the original model does. The performances of the three models are evaluated with reference to a set of recently published horizontal stress and permeability data measured under uniaxial strain conditions to simulate field conditions. The same set of data has been successfully matched using S&D model in an earlier study by the authors. The modelling results in this study show that both C&B and P&M models fail to capture the overall rising trend in the measured permeability, subject to the constraint of the horizontal stress variation recorded under uniaxial strain conditions. This may be attributed to the fact that the total horizontal stress varied with the pore pressure under the uniaxial strain conditions, whereas the total vertical stress remained unchanged during the test. The inability of C&B and P&M models to describe the laboratory permeability data obtained under simulated field conditions, in contrast to the performance of S&D model, suggests that the permeability response of coalbed reservoirs to pore pressure depletion is controlled predominantly by the effective horizontal stress, rather than the effective mean stress.

1. Introduction

Steady-state permeability of coal is known to be highly stress-dependent. Laboratory experiments and field measurements at different burial depths have shown that it generally reduces exponentially with increasing net confining/overburden stress (e.g., Durucan and Edwards, 1986; Mavor and Vaughn, 1998; McKee et al., 1988; Pan et al., 2010; Seidle et al., 1992; Somerton et al., 1974). During coalbed methane production through primary recovery, reduction in the reservoir pressure results in an increase in the effective stresses. Concurrently, desorption of coal gas (mostly methane) causes coal matrix to shrinkage, which has an opposite effect on the effective stresses of the coalbed reservoir. For a horizontally layered coal formation, the latter most likely affects only the effective horizontal stresses. Consequently, the permeability of coalbed undergoes dynamic changes during primary methane production, and is presumed to be controlled by the net effect of these two processes.

Since the late 80s of the last century, a number of analytical models have been proposed to describe the dynamic changes in coalbed permeability during methane production under uniaxial strain conditions considered to be prevailing in coalbed reservoirs (see Palmer, 2009; Pan and Connell, 2012 for a comprehensive review). Depending on whether the model equations are formulated around changes in reservoir effective stress or coalbed cleat porosity as the coalbed reservoir is being depleted, the permeability models may be broadly classified as either stress- or strain-based (Gu and Chalaturnyk, 2005).

The two widely used models are Palmer and Mansoori (1996, 1998) and Shi and Durucan (2004, 2005, 2010). Both models are developed to describe permeability change under uniaxial strain conditions prevailing in coalbed reservoirs. It is also assumed that the total vertical stress remains unchanged during coalbed methane (CBM) recovery. The P&M model first estimates change in the cleat porosity (expressed as the ratio to its initial value ϕ/ϕ_0) as the reservoir pressure is reduced, from which

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the cleat permeability change (also expressed as the ratio to its initial value k/k_0) is then computed using the well-known cubic law. In S&D model, on the other hand, the primary variable is the effective horizontal stress (σ_h). Change in the effective horizontal stress ($\Delta\sigma_h$) is first estimated, from which permeability change (expressed as the ratio to its initial value k/k_0) is computed as an exponential function of $\Delta\sigma_h$. The coefficient of the exponential relationship is termed cleat volume compressibility c_f, a key parameter in S&D model. Note that c_f used in the S&D model differs from the same parameter used by Seidle et al. (1992), which is highlighted later.

In an attempt to explain an apparent strong permeability rebound deduced from history matching the production data of a "Boomer" well in the San Juan Basin, Palmer and Mansoori (1996) showed that the rebound behaviour could be reproduced, at least qualitatively, by using a Young's Modulus value at the high end of its typical range for large scale San Juan Basin reservoirs (0.86 to 3.07 GPa) and a small initial cleat porosity (0.1%). Mavor and Vaughn (1998) showed that the well test derived permeability data from three CBM wells at Valencia Canyon area of San Juan Basin, which pointed to an increase in the absolute permeability as the reservoir pressure was reduced, could be matched using the P&M model and a pair of elastic properties (Young's Modulus = 3.6 MPa and Poisson's Ratio = 0.21).

McGovern (2004) reported a permeability multiplier curve, which depicts an increase in absolute permeability (expressed as a ratio over the value at ~800 psi (5.5 MPa)) as the reservoir pressure was reduced from 800 psi (5.5 MPa) to ~100 psi (0.7 MPa) estimated from history matching the gas production rates of a group of CBM wells located at the so-called Fairway in San Juan Basin. The initial reservoir pressure of these CBM wells was ~1600 psi (11.0 MPa). Shi and Durucan (2005) demonstrated that this permeability behaviour could be reproduced by the S&D model using a constant cleat volume compressibility when the reservoir pressure remained above ~200 psi (1.4 MPa), and a lower c_f when the pressure was further reduced while keeping other model parameters unchanged. In a more recent study, Shi and Durucan (2010) implemented a stress-dependent cleat volume compressibility, following McKee et al. (1988), in an effort to match the well test derived permeability data of 10 infill wells NE of the Fairway, each with three data points all displaying a near-exponential increase with reducing reservoir pressure (Gierhart et al., 2007). Permeability increase of up to one order of magnitude was observed from the well test data, and as high as two orders of magnitude was predicted, based upon model match of the field data, when the reservoir pressure is reduced to 100 psi (0.7 MPa).

In an attempt to describe more than one-order of magnitude increase in the absolute permeability observed in many wells in San Juan Basin, Palmer et al. (2007) proposed a modification to their original model, which was found unable to match all the field data by Gierhart et al. (2007). In the improved P&M model, a variable g is introduced to account for cleat anisotropy, allowing for the suppression of pressure-dependent permeability. Clarkson et al. (2010) applied the improved P&M model to fit the field gas permeability data on a Fairway well, estimated from production data analysis (Clarkson et al., 2008), which showed an approximately 10-fold increase in the effective gas permeability, from ~10 mD to ~100 mD, as the reservoir pressure was reduced from 932 psi (6.4 MPa) to ~100 psi (0.7 MPa) (the in-situ or virgin reservoir pressure was estimated to be around 1450 psi (10 MPa)).

In addition to P&M and S&D models, Cui and Bustin (2005) proposed an alternative permeability model, under the same subsurface conditions (uniaxial strain and constant total vertical stress), which assumes that coalbed permeability is controlled by the change in the mean effective stress (as opposed to the effective horizontal stress in the S&D model). The C&B model, as well as the P&M and S&D models, has been used to match the permeability data of coalbed wells from the Bowen Basin in Australia, estimated from analysing over 60 instances of data on pressure recovery during shut-in (Mazumder et al., 2012). Liu and Rutqvist (2010) developed a coal-permeability model for uniaxial strain and constant confining-stress conditions, which explicitly considers fracture–matrix interaction during coal-deformation processes and is based on an internal swelling stress concept. Other analytical models have also been proposed for different stress/strain conditions. Connell et al. (2010) developed a model for triaxial stress and strain conditions. Ma et al. (2011) presents a simplified permeability model for coalbed methane reservoirs based on matchstick strain and constant volume theory.

Both P&M and S&D models have been shown to be able to match the published field permeability data. So far, there has been no consensus as to which model represents the field permeability behaviour more accurately. This, to a large extent, is due to: 1) There are often limited site-specific data available for the parameters used in model match, especially the elastic properties of the coalbeds. and 2) the lack of additional stress/porosity change data to constrain the model parameters. Mitra et al. (2012) recently reported an experimental study of coal permeability behaviour under uniaxial strain conditions. As well as the permeability response to a declining pore pressure, the corresponding variation in the applied horizontal (radial) stress, which was adjusted throughout the test to maintain the laterally constrained boundary condition, was also measured.

The availability of both permeability and horizontal stress data under uniaxial strain conditions allows, for the first time, a more rigorous performance evaluation of the analytical permeability models to be made. Shi and Durucan (2014) have shown that the measured variations in both stress and permeability could be adequately described by the S&D model. In this study, an in-depth comparison between the four permeability models, namely the P&M model, S&D model, C&B model and the improved P&M model, focusing on the relative influence of the matrix shrinkage term over the compaction term in each model, is presented first. The performances of the P&M model, C&B model, and the improved P&M model are then evaluated against the laboratory stress/permeability data by Mitra et al. (2012).

2. Model comparison

The four permeability models are presented in Appendix A. Regardless of the difference in model formulation, the models essentially contain two opposing terms on cleat permeability with reducing reservoir pressure: a negative compaction term, resulting in a reduction in the permeability, and a positive matrix shrinkage term, resulting in an increase in permeability. The predicted dynamic permeability behaviour, in particular its overall trend over the life span of a producing coalbed reservoir, by each model is controlled by the competition between these two terms.

As shown in Appendix A, change in the primary variable in the four models, in response to reservoir pressure depletion from initial pressure p_0, can be expressed by a generic equation consisting of the two competing terms.

$$\Delta Q = Q - Q_0 = -A\Delta p + B\Delta\varepsilon_s \tag{1}$$

with

$$\Delta p = p - p_0, \quad \Delta\varepsilon_s = \varepsilon_s - \varepsilon_{s0} = \varepsilon_{smax}\left(\frac{p}{p+P_\varepsilon} - \frac{p_0}{p_0+P_\varepsilon}\right) \tag{2}$$

where Q is a generic variable representing cleat porosity or effective horizontal/mean stress, A and B are generic coefficients for the compaction and matrix shrinkage terms, ε_s and ε_{s0} are the matrix swelling strain at pressure p and p_0 (from zero pore pressure) respectively, ε_{smax} and P_ε are the maximum swelling strain and the pore pressure at which $\varepsilon_s = 0.5\varepsilon_{smax}$. It is implicitly assumed in Eq. (2) that the coalbed is saturated with adsorbed methane.