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A practical workflow for characterizing stress-dependent behaviour of coal from changes in well productivity

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ABSTRACT

Stress (or pressure) dependence of coal permeability is a commonly observed and generally accepted dynamic behaviour that is often ignored from production performance forecasting. Reasons for this omission typically include (a) the difficulties in reliably characterizing stress dependent effects from a limited number of pressure buildup (PBU) tests, and (b) large uncertainties in our understanding of both the porosity and compressibility of coals. This paper demonstrates a new analytical workflow, and proposes a new set of equations that overcomes some of those limitations. Engineers can use this paper to analytically translate expected permeability changes with pressure, to productivity changes with pressure differences.

This paper utilizes a slightly modified form of Palmer-Mansoori (P&M) model in a workflow that includes.

1. Estimation of coal cleat volume compressibility using permeability-depth trends.
2. Characterization of mechanical skins from interpreted apparent skins.
3. Calculation of stress dependent pseudo pressure (SDPP) – converting permeability changes with pressure to productivity changes with pressure differences – enabling the use of well productivities over time as part of a SDP characterization process.
4. The matching through regression of relative changes in well productivity indices in groups of wells - utilizing the SDPP approach – with a single stress dependent controlling parameter, in a way that is suited to extrapolating away from well control.

Theoretical support for this approach is provided via derivations from published models. A methodology is outlined – sharing the results of a field example – to demonstrate the relative ease with which the analytical process can be applied. Further, pitfalls are highlighted of using well productivities as a direct proxy for permeability changes, or even utilizing coarse grid numerical simulation in the matching process. Finally, further applications and limitations of its application are also discussed.

This paper addresses existing knowledge gaps in the coal bed methane (CBM) industry by providing a simple, yet efficient, workflow for characterizing and incorporating stress-dependence of permeability in CBM Reservoir Engineering. This is achieved through the application of new analytical equations to characterize stress dependent pseudo pressure, enabling the direct use of well productivity changes, and can be used standalone, or as a means to accelerate a numerical history matching workflow.

1. Introduction

Over the last decade, the Eastern coast of Australia has seen ground-breaking investments in the liquefied natural gas (LNG) industry, fueled by the abundance of CBM resource in onshore Australia and proximity to emerging energy markets. The combination of CBM wells with their low rates and unconventional decline behaviour with LNG plants and their large and uninterrupted gas demand, results in projects that depend heavily on the ability to predict well performance. However, quantification of well productivity indices (PI) and reservoir permeability - including its dynamic nature - is often challenging, with limited reservoir surveillance and production data often available for CBM reservoirs.

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Stress (or pressure) dependence of coal permeability is a commonly observed and generally accepted dynamic behaviour in coals that is often ignored from production performance forecasting. A significant reason for this is the difficulty in reliably characterizing stress dependent parameters with a limited number of pressure transient tests, and the large uncertainties in both porosity and compressibility of coals. Further, there exist significant challenges to representatively core and perform the types of laboratory tests than can reliably quantify the above properties due to the impact of the coring and recovery process on the core itself.

The state-of-the-art in CBM reservoir engineering techniques don't neglect the above mentioned issues. There are several published models [(Shi and Durucan, 2005) (Palmer and Mansoori, 1996), and (Pan and Connell, 2012) to name a few] that are able to quantify the dynamic permeability behaviour of coals with pressure. Most of the associated literature is also able to provide detailed discussion on coal cleat volume compressibility and porosity. However, there appears to be an existing knowledge gap in a practical and systematic workflow for estimation and inclusion of these coal properties in reservoir engineering analysis for coal reservoirs.

This paper;

1. Proposes a simplification to the P&M equation, enabling single shrinkage parameter behaviour matching
2. Integrates these simplified equations to a new form, enabling use of productivity behaviour to analytically match against
3. Proposes methods to fill typical data gaps
4. Outlines the application of the equations in a new workflow
5. Highlights other practical applications of the new equations and their implications
6. Briefly covers some of the main limitations and assumptions of this approach

2. Methodology

The theoretical development and the associated numerical modeling methods used to test the theory are covered in the relevant sections of this paper.

3. Theory

3.1. Simplification of the stress-dependent coal permeability formulation

In a review of available coal permeability analytical models and testing data, Pan and Connell (2012) provide an extensive discussion on available models, their assumptions and their differences. In concluding remarks, they call for a balance in the ability to meaningfully estimate properties in model vs the detail and complexity of the models. This comment resonated with the authors of this paper, having grappled with the number of unique model parameters, complex coal permeability behaviour and the sheer number of poorly understood factors that affect it. This is also evident in the revisions made to two of the most accepted analytical models by their respective authors, as they have continued to refine them with latest understanding [(Shi and Durucan, 2009) (I. Palmer, 2009),].

The work in this paper does not add to the crowded list of stress dependent permeability models, rather, it first provides a simplification of an existing model (P&M model) to aid in its practical application. It then follows by integrating it, transforming an equation that characterizes permeability changes as a function of pressure, to one that characterizes productivity changes as a function of pressure differences. Finally, it details the application of these equations in a workflow, along with methods to help fill data gaps.

As outlined by Burgoyne and Shrivastava (2015) an alternate derivation of the P&M model equation (Palmer and Mansoori, 1996) can be shown to evaluate to equation (1).

$$\frac{\varnothing}{\varnothing_0} = \mathrm{e}^{-c_f(p-p_0)} + \left(\frac{B}{\varnothing_0} \times \varepsilon_l\right) \times \left[\left(\frac{p_{sat}/P_L}{1+p_{sat}/P_L}\right) - \left(\frac{p/P_L}{1+p/P_L}\right)\right] \tag{1}$$

This can be simplified by assuming that maximum strain ε_l, depends on both the adsorption capacity of the coal, and the insitu density of adsorbed methane. Density of adsorbed methane (adsorbate) has been found to be close to the reciprocal Van der Waals volume, with many experimental studies finding 373 kg/m^3 a reasonably good fit (Gensterblum et al., 2013) and (Sakurovs et al., 2012).

Assuming then that the absolute pore volume created due to desorption can be no greater than the insitu volume of the released adsorbate, the product of $B^*\varepsilon_l$ can then be represented by $B \times \varepsilon_l = f \times 7.2 \text{ x } 10^{-5} \times V_L$, where f is a bounded fraction between 0 and 1, representing the fraction of adsorbate volume that converts to an increase in available flow-affecting pore volume. With methane density under standard conditions = 0.662 kg/m^3, and adsorbate density = 373 kg/m^3, the methane formation volume factor = 0.001775 rcm/scm. Multiplying this by a coal density @ 1.3 tonne/rcm yields a volume conversion factor = 0.002307 tonne/scm or 7.2×10^{-5} ton/scf.

Equation (1), then, can be written as

$$\frac{\varnothing}{\varnothing_0} = \mathrm{e}^{-c_f(p-p_0)} + \left(\frac{f}{\varnothing_0} \times V_L \times 7.2 \times 10^{-5}\right) \times \left[\left(\frac{p_{sat}/P_L}{1+p_{sat}/P_L}\right) - \left(\frac{p/P_L}{1+p/P_L}\right)\right] \tag{2}$$

Given that the degree of shrinkage in equation (2) is proportional to $(f/\varnothing_0)$, and assuming that the commonly used permeability relationship with the cube of porosity ($k = A\varnothing^3$) applies, then equation (2) can be re-written as equation (3) by further moving V_L and the volume conversion factor to the right of the equation, which makes clear that for given a change in gas content and a value of initial permeability, the degree of shrinkage is proportional to a single group $(f\sqrt[3]{A})$.

$$\frac{\varnothing}{\varnothing_0} = \mathrm{e}^{-c_f(p-p_0)} + \left(f\sqrt[3]{A}\right) \times \left[7.2 \times 10^{-5} \frac{\left(GC_i - \frac{V_L \cdot P}{P_L+P}\right)}{\sqrt[3]{k_0}}\right] \tag{3}$$

The significance of this simplified form of P&M model is that.

1. Geomechanical shrinkage characteristics of the coal are compressed to a single regression group $(f\sqrt[3]{A})$
   1.1. taking into account both the shrinkage behaviour as well as the permeability vs porosity relationship, greatly simplifying the matching process