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Laboratory measurement and modeling of coal permeability with continued methane production: Part 1 – Laboratory results

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ABSTRACT

This paper, first of a two-part series, discusses the results of a laboratory-scale study completed to establish the permeability variation trend with continued production of methane from coal-gas reservoirs. The field condition of uniaxial strain, assumed in the analytical models developed for permeability prediction, was replicated in the study. The results showed that the permeability of coal increases continuously, the rate of increase accelerating at low pressures. The primary reason for the increase appears to be the decrease in horizontal stress resulting from the sorption-induced volumetric strain, the so called "matrix shrinkage" effect. In the second part, experimental data is used to validate the commonly used permeability prediction analytical models and present a modification for one to improve its ability to predict permeability changes.

1. Introduction

Increase in coalbed methane (CBM) production in the US has been truly significant since the early eighties, from near zero in 1980 to almost two trillion cu ft (TCF) in 2009. Interest in this resource continues to grow worldwide, with significant activity in Australia, Canada, China and India. With increased experience with CBM production, it has become abundantly clear that the permeability of coal varies with continued production. The most dramatic examples of this are several producing reservoirs in the San Juan Basin, with permeability increases of as much as 100 times.

During drawdown of a reservoir by primary production, effective stress is believed to increase, resulting in permeability reduction due to the closure of cleats. However, methane is stored in coal as sorbed gas and production leads to desorption of gas. This is accompanied by "matrix shrinkage", which is believed to open up the cleats, thus leading to increased permeability. In order to predict the overall changes in permeability with depletion and project long-term gas production, several models have been developed taking into account these two effects. Effort to validate these models using production data has only been partially successful and has required "tweaking" of the input parameters, somewhat defeating the purpose of modeling. Since the models are based on fundamental principles of poro-elasticity and geomechanics, and their application is independent of size, laboratory derived data has also been used for model validation. This has had only limited success, primarily because the experimental conditions did not replicate the underlying principles and assumptions of the models properly, raising serious questions about the value of the validation exercise.

This paper, first part of a two-part series, presents the results of a study, where permeability variation of core of coal taken from the San Juan basin was established as a function of decreasing pressure. The experimental conditions not only best replicated *in situ* conditions but were also identical to the founding principles used for development of the recent theoretical models. This is the first reported experimental study where flow measurements were made while coal was held under uniaxial strain condition, that is, the sample was not permitted to physically shrink as a result of desorption, just like it does not under *in situ* condition due to lateral confinement. Instead, the horizontal stress was adjusted when the core started to shrink, ensuring zero horizontal strain. As a separate effort, volumetric strain associated with sorption of gas was measured to obtain appropriate parameters for modeling. The second part of this effort includes application of two models most commonly used in the San Juan basin to predict permeability changes and comparison of the experimental and modeled results, and concludes by providing an insight to the strengths and weaknesses of the models.

2. Background

2.1. Structure of coal

Coal is generally characterized as a dual porosity rock, containing both macropore and micropore systems, as shown in Fig. 1a.

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The macropore system consists of a naturally occurring network of fractures called cleats, serving as the primary pathways for gas transport. The microporosity of coal is within the coal matrix blocks, surrounded and separated by cleats, consisting of large number of interconnected pores that serve as the storehouse for methane in adsorbed form. For the purpose of gas flow modeling in CBM reservoirs, coal structure is best described by a bundle of matchstick model, as shown in Fig. 1b [1], with each matchstick representing a block of coal matrix, whereas the cleats are represented by the void space between the matchsticks.

2.2. Coal permeability

With continued gas production from a CBM reservoir, the effective stress is believed to increase. The phenomenon of stress-dependent permeability has been studied and reported by several researchers [2–6]. Typically, an exponential decrease in permeability with increasing stress has been reported. Along with increased effective stress, the sorption-induced volumetric strain of coal matrix is believed to result in increased permeability. Matrix shrinkage is a universal phenomenon and all coals shrink when releasing sorptive gas [7–10]. The associated increase in coal permeability was first hypothesized by Gray [11], which was first verified experimentally by Harpalani and Schraufnagel [10], and confirmed in a subsequent study, clearly demonstrating an overall increase in permeability [12]. It was also shown that the sorption-induced volumetric strain is a non-linear function of pressure [13], later confirmed by Levine [14]. Furthermore, field measurements of permeability variation with continued production in the San Juan basin have shown increases of orders of magnitude in some CBM reservoirs [15–18]. The trend of this increase, however, has been reported to be either continuous or L-shaped where the rate of increase is low initially, followed by a sharp increase at lower pressures. Finally, shrinkage of coal matrix with desorption is also believed to reduce the effective horizontal stress, opening up the cleats further and thus increasing the permeability significantly [16].

2.3. Previous laboratory studies

All previous studies completed in the laboratory used stress-controlled conditions, where the sample was allowed to deform axially as well as laterally. The first laboratory study reporting the effect of matrix shrinkage on permeability increase was that of Harpalani and Schraufnagel [10]. They reported an initial decrease in methane permeability with decreasing gas pressure up to a point. However, with further reduction in gas pressure, permeability started to increase. Based on this, they concluded that permeability increases only after the rate of desorption becomes significant. This was later confirmed by measuring helium permeability that showed a continuous decrease with decreasing gas pressure [10] since helium is non-sorptive. In a separate study, Harpalani and Chen [12] concluded that the change in permeability associated with matrix shrinkage was linearly proportional to the

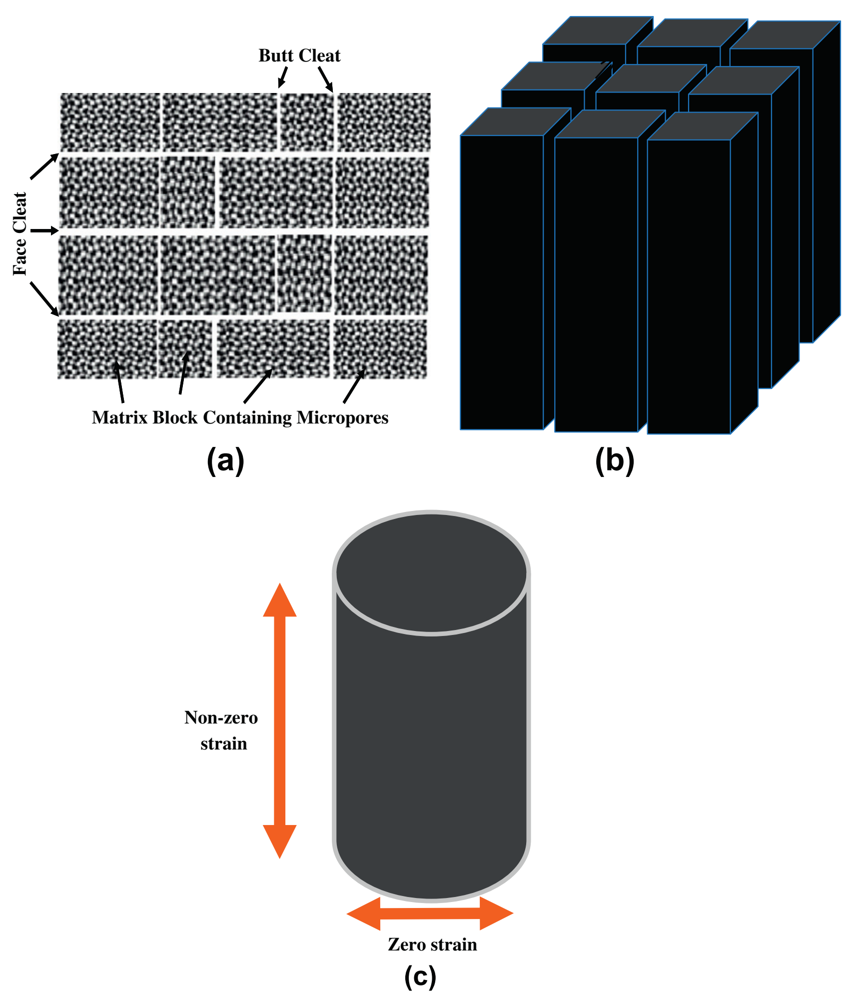

Fig. 1. Physical structure, model of coal and concept of uniaxial strain.