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Laboratory measurement of stress-dependent coal permeability using pulse-decay technique and flow modeling with gas depletion

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ABSTRACT

A laboratory-scale coal permeability measurement study using the pressure pulse decay method was carried out to establish the permeability variation trend impacted by the combined effects of effective stresses and coal matrix shrinkage associated with gas depletion under uniaxial strain condition for San Juan basin coal. The experimental results showed that increased effective horizontal stress negatively impacts permeability enhancement. Furthermore, effective horizontal stress dominates the permeability variation. Finally, the rate of permeability increase accelerates dramatically at low pressures as a result of decrease in effective horizontal stress due to the matrix shrinkage effect. The established pressure-dependent-permeability (PdK) was compared with modeled results using two models, Harpalani and Chen and Shi and Durucan, both based on variations in effective horizontal stress. The match with the results obtained using the Harpalani and Chen model was perfect when appropriate initial cleat porosity and matrix shrinkage strain parameters were used. However, given the analytical conditions presented, the agreement between experimental and modeled results using the Shi and Durucan model was poor. After reviewing the fundamental principles behind model development, a modification was made, based on geo-mechanical principles. The measured permeability variation matched well with the results predicted by the modified model when appropriate cleat compressibility values were used. Basically, the revised model increases the effect of matrix shrinkage on permeability changes with continued depletion. The modeled results showed a permeability trend consistent with the experimental result although the permeability of coal was overestimated at low pressures.

0. Introduction

Recovery of methane trapped in coal economically has been evident since the early 1980s, when production in the US, primarily the San Juan and Black Warrior basins, started to increase at an accelerated pace [1]. Commercial production of coalbed methane (CBM) is now well established in several countries, such as, US, Canada, Australia, China and India, with test/pilot program underway in several other countries. Successful CBM production is attracting world-wide attention as a cheap and clean source of energy. CBM producibility depends on several factors, such as, coal thickness, gas saturation, rank of coal types, and geologic settings, the most important and controlling one being coal permeability.

Stress-dependent permeability (σdK) has been studied and reported by several researchers, both at the laboratory and field scales [1–15]. The effective stress, a key parameter of concern to CBM operators, because of its unusual variation with continued production, is closely related with permeability variation. Coal reservoir permeability behavior is similar to other fractured reservoirs with respect to effective stress, decreasing dramatically as the effective stress increases. However, a unique feature of coal is that it shrinks with gas desorption, and the desorption-induced shrinkage strain leads to a geo-mechanical response, further changing the effective stress and thus the permeability. Gray [7] first hypothesized increase in permeability due to the effect of desorption-induced shrinkage, which was then experimentally verified by Harpalani and Schraufnagel [16], and confirmed further in subsequent studies [17,18].

This paper presents the results of a study carried out on core of coal, taken from the San Juan basin, where dynamic deformation behavior of coal associated with gas depletion and its impact on permeability variation were established as a function of effective stresses. The permeability measurement technique, pressure pulse decay method (PDM), was first employed under uniaxial strain condition to establish the pressure-dependent-permeability (PdK) for San Juan basin coal. This experimental condition is believed to not only best replicate *in situ* gas flow condition but is also con-

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sistent with the basic principles used for the development of current widely-used analytical models. Finally, due to uncertainties or shortcomings in previously developed models, a modified analytical model was developed to predict the permeability changes with depletion. For the purpose of comparison, the permeability results of this study were compared with the experimental work conducted by Mitra et al. [19] and Liu [20] using the steady-state flow method (SFM) under the same experimental conditions.

1. Background

1.1. Physical structure of coal

Coalbed methane reservoirs are characterized as naturally fractured, dual porosity, low permeability, and water saturated gas reservoirs [21], consisting of primary and secondary storage and mass transport systems [16]. The primary porosity system serves as the major residence for adsorbed gas in coal, where over 95% of the gas is in adsorbed phase [7]. The secondary porosity system (cleat system) provides the primary pathways for gas and water flow in coal. Free gas resides mainly in the cleat system that accounts for major part of the permeability for fluid flow in coal.

There are two types of cleats in coal: face cleats and butt cleats [22], as shown in Fig. 1 (cubic element). These two are commonly mutually orthogonal, or nearly orthogonal, and are perpendicular, or nearly perpendicular, to the bedding planes. For the purpose of gas flow modeling in CBM reservoirs, a common naturally fractured reservoir geometry represented as a collection of matchsticks was first extended to stressed coalbeds by Seidle et al. [1], with each matchstick representing a block of coal matrix and the cleats represented by the apertures between matchsticks.

1.2. Laboratory studies of coal permeability

For laboratory testing of permeability, there are two commonly-used techniques: steady-state flow method (SFM) and pressure pulse decay method (PDM). The basic principle of both methods is the Darcy's law, commonly applied when analyzing experimental results. In order to estimate the cleat permeability behavior of coalbed reservoirs, a number of permeability tests have been performed and reported in the literature. Both Patching [23] and Gunther [24] observed a decrease in permeability of three orders of magnitude under varying confining stress conditions. Results reported by Somerton et al. for coal [5], obtained under hydrostatic stress condition, showed that permeability was highly stress-dependent. Harpalani and McPherson [2] conducted coal permeability tests with respect to different stress conditions and reported linearity between hydrostatic stress and the logarithm of permeability. Durucan and Edwards [3] reported changes in permeability of coal, subjected to stress, to be caused by the combined result of the compression of pores and micro-fracturing. Based on the observation that permeability decreased first and then increased sharply under constant hydrostatic stress condition, Harpalani and Schraufnagel [16] hypothesized that coal permeability increases only after significant desorption starts. Harpalani and Chen [11] investigated the effect of gas slippage and matrix volumetric strain on coal permeability and reported significant increases with decrease in pressure as a result of both matrix shrinkage and gas slippage. Robertson [25] carried out a series of permeability experiments under constant confining stress and reported similar results as Harpalani and Schraufnagel [16]. Pan et al. [26] reported that the permeability decline with pore pressure is a direct result of adsorption induced coal swelling under hydrostatic stress condition. In 2011, the study completed by Mitra et al. [19] was the first-of-its-kind where permeability of core of coal was measured under uniaxial strain condition. In subsequent studies, Liu [20] and Singh [27] clearly demonstrated that coal permeability increases non-linearly with continued methane depletion, and an uptick may be observed when pore pressure falls below a certain level.

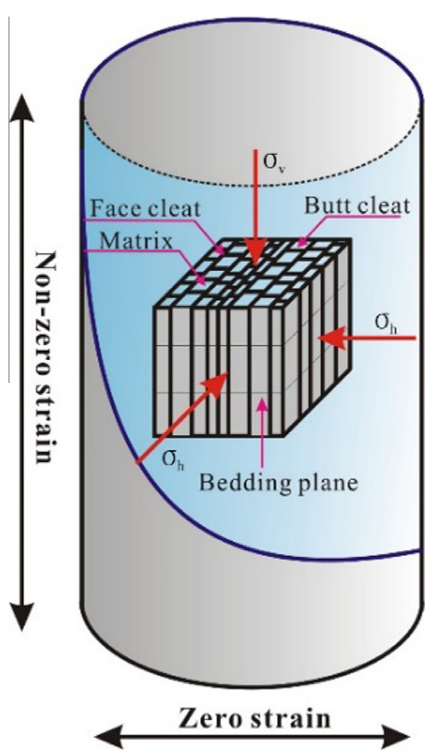

Fig. 1. Physical structure of coal and concept of uniaxial strain.

1.3. Concept of uniaxial strain

Fig. 2 presents three commonly-used experimental conditions for permeability measurement, including both stress-based and strain-based testing. Fig. 2(a) shows the constant volume condition, where all the external boundaries are confined. Fig. 2(b) represents the uniaxial strain condition, where lateral strain is constrained as zero and the vertical stress is maintained constant with gas depletion. Fig. 2(c) presents the hydrostatic stress condition, which is the basis of several laboratory experiments reported in the literature.

Uniaxial deformation, regarded as a typical status of CBM reservoirs, was first introduced to CBM field by Seidle et al. [1], where strain induced by depletion of reservoir pressure only occurs in the vertical direction because of zero strain maintained laterally. As illustrated in Figs. 1 and 2(b), the core would experience non-zero strain in the vertical direction and zero strain in the in horizontal direction. No strain is allowed in the lateral direction during permeability measurement, ensured by reducing the horizontal stress to compensate for the matrix shrinkage. This is a major deviation from most of the previously reported studies that used hydrostatic stress condition. Thus, the current study is conducted under uniaxial strain condition, as performed by Mitra et al. [19], Liu [20] and Singh [27].

2. Experimental section

2.1. Experimental principle

The pressure pulse-decay method (PDM), first proposed by Brace et al. [28], was used for the flow experiments in this study.