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Stress path with depletion in coalbed methane reservoirs and stress based permeability modeling

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ABSTRACT

That permeability is a critical parameter dictating the performance of naturally fractured reservoirs, like coalbed methane (CBM), is evident form the available field, experimental and permeability modeling information in the literature. Although modeling is often achieved at the expense of several input parameters, the exercise is typically unable to match sudden increases in coal permeability, encountered in deep coals after significant depletion. This paper is aimed at coupling stress and permeability in order to reduce the number of parameters required for modeling the permeability variation. Stresses in the reservoir are translated to invariants and stress path of coal is established in octahedral effective stress plane. Based on a detailed analysis of the stress path of three different coal types, a permeability model is presented in terms of stresses alone, that is applicable for elastic as well as inelastic deformations of coal. The model is validated using pressure-dependent-permeability experimental data for three coal types along with the geomechanical testing data used to develop the failure envelope. The primary implication of the study is improved capability to predict permeability of deep coal deposits, given that they are likely to undergo inelastic deformation or shear failure with continued depletion, using one parameter only. Finally, realistic constraints on the values of the parameter are provided to enable operators with the necessary tools to use the model for field applications, particularly in the new and upcoming CBM fields.

1. Introduction

Coal gas reservoirs are considered naturally fractured, typically with a well-developed fracture network, known as the cleat system (Laubach et al., 1998). The cleats are primarily responsible for the permeability in coalbed methane (CBM) reservoirs and the performance of a reservoir depends largely on this parameter. Furthermore, it is well accepted that coal permeability changes dynamically throughout the life of a reservoir, depending on the variation in reservoir stresses. Two different dynamics are believed to affect the permeability of CBM reservoirs. First, the mean effective stress increases with depletion, inducing compaction in the reservoir and thus leading to a decrease in its permeability. Second, with depletion of methane, coal matrix shrinks, resulting in lateral relaxation of the coal matrix and fractures and, hence, in increased permeability. These two processes, dominant in the elastic deformation zone of the reservoir, occur simultaneously.

Sorption-induced coal matrix shrinkage is a well understood phenomenon, with tremendous amount of information in the literature describing it. Since methane is in adsorbed state in the coal matrix, there is an increase in the surface energy of pore surfaces of coal (Brochard et al., 2012; Espinoza et al., 2013; Kowalczyk et al., 2008; Pijaudier-Cabot et al., 2011). On macroscopic scale, this effect translates to swelling of the coal matrix. Hence, during depletion of methane, coal matrix shrinks, resulting in opening up of the cleats and increased permeability (Ceglarska-Stefańska and Zarbska, 2002; Cui and Bustin, 2005; Harpalani and Chen, 1997; Harpalani and Schraufnagel, 1990; Karacan, 2007; Lin and Kovscek, 2014; Liu et al., 2011; Mazumder et al., 2006; Pan and Connell, 2007; Wang et al., 2010). The second effect of coal matrix relaxation is a reduction in the horizontal stress with continued depletion.

There have been several studies and permeability models presented in the literature, coupling the phenomena of stress and permeability of CBM reservoirs (Cui and Bustin, 2005; Liu et al., 2012; Palmer and Mansoori, 1998; Sawyer et al., 1990; Shi and Durucan, 2010, 2005, 2004). However, most modeling work has concentrated on the elastic deformation, with little on post-failure modeling. It is important to note that deep coals (> 1000 m), such as, Sanga Sanga basin Indonesia, parts of San Juan and Greater Green River basins in the US and some coals in China are typically under significant stress conditions (vertical stress > 20 MPa, using the lithostatic rule of thumb), and depletion

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may result in inelastic deformation.

Under appropriate conditions, this may also result in shear-induced failure in the reservoir (Chen et al., 2016; Liu and Harpalani, 2014; Saurabh et al., 2016). Some studies suggest that such inelastic deformation and shear failure result in significant permeability boost of CBM reservoirs (Chen et al., 2016; Espinoza et al., 2015; Liu and Harpalani, 2014; Singh, 2014). In deeper parts of the San Juan basin, such increases in permeability have been encountered in CBM operations (Okotie and Moore 2011). Sudden decrease in permeability is also known to occur, accompanied by production of large amounts of fines requiring well cleanouts, following which, permeability continues to increase. Previous attempts to delineate stress and deformation coupling in coal with depletion are fairly detailed (Espinoza et al., 2015; Liu and Harpalani, 2014; Lu and Connell, 2016). However, they lack completeness in terms of identifying the complete stress path of coal with depletion. In addition, past studies lack rigorous validation in terms of application of the theory to different coal types.

There are only a few studies in open literature that address the variation in permeability over the range of elastic, inelastic and post-failure deformations. Chen et al. (2016) presented such a model although it was based on logistic function with the aid of three fitting parameters in order to achieve a good fit. The three parameters, however, were without constraints. In this paper, we first attempt to lay the ground by establishing the stress path for different coal types. Following this, we present a detailed analysis of the stress path to generalize the observations. The analysis is then used to discuss the nature of stress path of different coal types. The stress path is then shown to be coherently related to permeability data because several features of the variation of the two are strongly coupled. In light of the stress path investigation and observations made for the coal types, a general permeability model for coal is developed and presented. The proposed permeability model is useful in predicting permeability in elastic as well as inelastic deformation zones of CBM reservoirs. The model was able to predict experimental permeability variation accurately using a proposed modeling parameter, which encompasses the information on the stress path. Although the parameter is essentially a fitting parameter, effort to place constrains on its value within reasonable bounds, and using experimental data to estimate its value, is presented. This can be a useful guideline for the modeling exercise presented and serve as a tool for permeability and production modeling of the recent and upcoming CBM reservoirs in the San Juan basin.

2. Experimental work and results

2.1. Experimental work

Experimental data used for the analysis presented in this paper is taken from a laboratory-based study completed at Southern Illinois University, aimed primarily at establishing the pressure-dependent-permeability (PdK) of CBM reservoirs in the San Juan basin in the US and Sanga Sanga (SS) basin in Indonesia (Saurabh et al., 2016; Soni, 2016; Singh, 2014). The experimental work was carried out to determine the changes in permeability with pressure drawdown, ensuring best possible replicating *in situ* reservoir stress and uniaxial strain conditions. *In situ* conditions were replicated using a triaxial setup, where the core was stressed to *in situ* vertical stress condition. The two horizontal stresses were assumed to be equal and the initial horizontal stress condition was estimated assuming normal faulting regime for the coal type. The above assumptions are appropriate for Sanga Sanga (SS) and San Juan Coal (SJM/SJSJ) basins. Over the course of the experiments, stresses, strains, P-wave velocity and flowrates were recorded for a step-wise decrease in gas pressure, first using helium and then methane, for each depletion step. In addition, triaxial strength testing of the coal type was carried out under incremental confining stress conditions to establish the failure envelope for the coal type. The geomechanical test results also provided the mechanical parameters, Poisson's ratio, Young's modulus, cohesive strength and friction angle. Details of all experimental setups and testing procedures are presented in Saurabh et al. (2016) and Singh (2014).

Table 1
Sample location and rank of coals tested.

Sample name	Location	Rank of coal
SJM	Northwestern San Juan basin, US	Sub-bituminous
SJSJ	Northwestern San Juan basin, US	Sub-bituminous
SS	Sanga Sanga basin, Indonesia	Sub-bituminous

Table 2
Proximate analysis results for coals tested.

Sample name	Density (g/cm^3)	Ash content (%)	Moisture content (%)
SJM	1.34	5.1	7.9
SJSJ	1.31	7.9	1.4
SS	1.26	1.2	4.8

2.2. Sample characterization

The coal tested in this study was retrieved from different parts of the world and geologic settings. Table 1 presents the details of the sample location and geology. The rank of all coals tested was sub-bituminous. Table 2 presents the ash, moisture content and density of the coal types. Core of coal, two inches in diameter and three inches long from San Juan basin (SJM and SJSJ), and four inches in diameter and six inches long from Sanga Sanga basin (SS), were used for the flow testing. Cores two inch in diameter and four inches long were used for geomechanical and failure envelope testing. Pictures of coal cores ends showing their cleated structure are presented in Fig. 1.

2.3. Experimental results

Initial stress conditions for the experiments were based on the normal stress regime (Zoback, 2007). The boundary condition for the flow experiments was uniaxial strain. Hence, the total vertical stress, replicating the depth of coal, was maintained constant throughout the experiment and no horizontal strain was allowed during depletion. The latter condition was realized by changing the horizontal stress during the period when coal was equilibrating (pressure and strain) for each pressure step. However, release of methane and its depletion resulted in matrix shrinkage, resulting in significant horizontal strain, which was compensated for by decreasing the total horizontal stress. Starting with initial horizontal/vertical stresses and pore pressure, the horizontal and vertical stresses were monitored with step-wise depletion of methane. The variation in stresses over the duration of the experiments is shown in Fig. 2. Since the primary aim of the study was to establish the pressure-dependent-permeability (PdK) trend with depletion, permeability was estimated using the measured flowrates for each step. Fig. 3 presents the variation of permeability (k) with methane depletion as a function of the initial permeability (k_0). For the experiments using San Juan coal, the core underwent shear failure whereas the SS coal did not. Fig. 4 presents the pictures of the failed core after the flow testing was completed. Table 3 presents the geomechanical strength data for the coal types. Each permeability experiment took approximately five months to complete due to the long equilibrium time (typically 4–8 days) for each pressure step.

Fig. 2 shows the changes in horizontal stress with methane depletion. It clearly exhibits a continuous decrease in the horizontal stress while the applied vertical stress remained constant, ensuring uniaxial strain condition. The overall trend of decreasing horizontal stress with depletion is the same for all three cores tested although the rate of decrease is fairly similar for San Juan coals, but different for SS coal.