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# Laboratory investigations of gas flow behaviors in tight anthracite and evaluation of different pulse-decay methods on permeability estimation

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ABSTRACT

Permeability evolution in coal is critical for the prediction of coalbed methane (CBM) production and $CO_2$-enhanced-CBM. The anthracite, as the highest rank coal, has ultra-tight structure and the gas flow dynamics is complicated and influenced by multi-mechanistic flow components. Gas transport in anthracite will be a nonlinear multi-mechanistic process also including non-Darcy components like gas as-/desorption, gas slippage and diffusion flow. In this study, a series of laboratory permeability measurements were conducted on an anthracite sample for helium and $CO_2$ depletions under both constant stress and uniaxial strain boundary conditions. The different transient pulse-decay methods were utilized to estimate the permeability and Klinkenberg correction accounting for slip effect was also used to calculate the intrinsic permeability. The helium permeability results indicate that the overall permeability under uniaxial strain condition is higher than that under constant stress condition because of larger effective stress reduction during gas depletion. At low pressure under constant stress condition, $CO_2$ permeability enhancement due to sorption-induced matrix shrinkage effect is significant, which can be either clearly observed from the pulse-decay pressure response curves or the data reduced by Cui et al.'s method. But within the same pressure range, there is almost no difference between Brace's method and Dicker & Smits's method. Gas slippage effect is also significant at low pressure for low permeability coal based on the obtained experimental data.

## 1. Introduction

In the United States, the development of coalbed methane (CBM) was initially encouraged by federal tax incentive during the early 1980s. Since then CBM was considered as a valuable clean energy resource, and the most recent annual energy report by the US Energy Information Administration (Markowski et al., 2014) reveals an incredible increment in coalbed methane production from 1989 to 2008 (Fig. 1). Although after 2009 the production rate shows a little decline trend, CBM is still an important natural gas production contributor. In the US, Pennsylvania is the fourth largest coal producing state in the nation in 2014 and the only state producing anthracite coal. Anthracite coal has a general higher heating value than other coal types (Coal Age, 2014). The anthracites were known as ultra-tight and also the highest rank coal with the highest fixed carbon content. Additionally, from an environmental standpoint, $CO_2$ sequestration in anthracite coal seams is also attractive due to the high $CO_2$ holding capacity per unit volume/mass. For both anthracite-CBM and $CO_2$-enhanced CBM, the permeability of coal is one of the key decision-making parameters and thus a sound knowledge of the permeability evolution for anthracites will be essential.

During CBM production, the permeability of coal dynamically changes as a result of pressure drawdown. When pressure decreases, there will be an increase of the effective stress, defined as the difference between the external stress and pore pressure, tending to close the aperture of existing fractures (Cui and Bustin, 2005; Mazumder and Wolf, 2008; Palmer and Mansoori, 1998; Shi and Durucan, 2004; Wang et al., 2012a; Wang et al., 2012b; Wang et al., 2011). And the pressure drawdown also results in coal matrix shrinkage through a thermodynamic energy balance which tends to open the factures and an enhancement of permeability (Liu and Harpalani, 2013a, 2013b; Pan and Connell, 2007). The permeability evolution is, therefore, controlled by two competitive effects, namely, stress induced permeability reduction and matrix shrinkage induced permeability enhancement during pressure depletion. What's more, gas flow in anthracites is expected to be influenced by multi-mechanistic flow dynamics such as sorption, diffusion, slippage and, Darcy flows (Javadpour, 2009). The non-Darcy flows could be significant in anthracites because of the extremely tight matrix structure when the mean gas flow path is comparable with the pore size. Thus, the estimated permeability by assuming only Darcy's flow may not be valid for tight anthracites with non-ideal gases like $N_2$, methane and $CO_2$ (Gensterblum et al., 2014), and the characterization of non-Darcy components raises its importance for both laboratory measurements and modeling.

In this paper, the transient method "pulse-decay" technique was used to measure the low permeability on anthracite sample (Brace

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et al., 1968). However, this original pulse-decay method has its limitations when applying to coal or other organic-rich reservoir rocks. For example, it assumes no compressive storage in the rock sample (Hsieh et al., 1981), pure Darcy's flow components without sorption effect (Cui et al., 2009) and no gas slippage effect (Heller et al., 2014). Thus in this study, both pulse-decay approaches with pore compressive storage effect developed by (Dicker and Smits, 1988) and with sorption effect developed by (Cui et al., 2009) will be employed along with the classic pulse-decay and Klinkenberg correction will be introduced to weigh the contribution of slip flow, in order to test how non-Darcy effect would impact the tight coal permeability. Also, the permeability was measured under various experimental boundary conditions and the influence of different boundaries was discussed in detail.

## 2. Background and literature review

### 2.1. Anthracite-CBM studies

Coal is generally considered as a self-source reservoir rock with high gas storage capacity due to sorption effect. Anthracite, as the highest rank coal, has higher adsorption capacity for gas storage than lower rank coals (Markowski, 2014). However, anthracite coal has a relatively low porosity due to high thermal maturity. Thus the lessons learned from fluid dynamics in tight-shale may help us to better understand the permeability evolution of anthracite coal. The past coal permeability studies on anthracites showed complex permeability behaviors with combined matrix swelling/shrinking and effective stresses effects (Izadi et al., 2011; Wang et al., 2011; Yin et al., 2013). Also, gas transport in anthracites is a multi-mechanistic process including sorption, diffusion, slip and advection flows. Therefore, a comprehensive characterization and evaluation of anthracite coal permeability evolution in laboratory scale is critical to decipher the complexity of gas and coal interactions during CBM/ECBM production.

### 2.2. Compressive storage and sorption effect on coal permeability

Compressive storage of the reservoir in pulse-decay permeability measurements is influenced by instantaneous volumetric flow rate change, pressure drop rate and fluid and reservoir compressibility (Jones, 1997). The original pulse-decay developed by Brace et al. (1968) assumed no compressive storage effect in rock sample. Hsieh et al. (1981) then derived a general solution accounting for the compressive storage effect in pulse-decay, and Dicker and Smits (1988) presented a new model to apply this effect into pulse-decay method. The significance of this effect depends on the ratio between the compressive storage inside the sample and in the up-/downstream reservoirs, which means it needs to be evaluated case by case. Since both Brace's method and Dicker & Smits's method have been widely applied in sample permeability measurements, the feasibility of each method, in our case, should be deliberately tested for ultra-tight rocks.

As a primary storage mechanism in CBM reservoirs, adsorption is, especially, necessary for indirect gas content estimation (Hartman, 2008). Gas sorption capacity is typically influenced by pressure, temperature, microstructure of the rock, and it is further found that the absorbed amount of gas is proportional to the organic carbon content of the rock (Hildenbrand et al., 2006; Pillalamarry et al., 2011; Walls et al., 2012; Zhang et al., 2012). For coals, adsorption has indirect influence on gas transport properties (Cui et al., 2009). Permeability is a factor measuring the ability of fluid flow through a porous medium following Darcy's law (Mckernan et al., 2014). During CBM production, methane molecules desorb from the internal surfaces of matrix resulting a matrix shrinkage that opens natural cleats and then increase of permeability (Liu and Harpalani, 2014a; Mitra et al., 2012). In (Liu and Harpalani, 2013a), both mechanical effect and sorption induced strain during reservoir depletion was combined in a sorption-induced strain model that can be coupled into existing permeability models (Liu and Harpalani, 2013b). This coupled model was tested to be valid for subbituminous coal. However, the roles of sorption effect on the high rank anthracite permeability has not been investigate and quantified.

### 2.3. Pulse-decay method for stressed rock permeability estimation

Significant experimental work has been tried to measure the permeability and its evolution in coal and other tight rocks. Brace et al. (Brace et al., 1968) firstly introduced the pulse-decay technique as a transient method derived from Darcy's law to simply measure the permeability by applying a pressure difference between two sides of a core sample. After the initial pulse-decay method was introduced, this technique has been extensively applied for the tight rock permeability estimation. Different data interpretation methods were used by different scholars and they were summarized in Table 1 (Cui et al., 2009; Dicker and Smits, 1988; Jones, 1997; Kamath et al., 1992; Luffel et al., 1993; Malkovsky et al., 2009; Wang et al., 2011). Dicker and Smits (1988) proposed a pulse-decay calculation method with pore volume compressive storage effect correction. However, they didn't incorporate any adsorption effect and non-Darcy flow regimes into the calculation to be suitable for the unconventional gas permeability measurements. Moreover, laboratory estimation of permeability of unconventional reservoir rocks with adsorption effect has been reported and it has been traditionally measured either under hydrostatic conditions (Cui et al., 2009; Soeder, 1988) or in the absence of applied stress (Cui et al., 2009). In (Cui and Bustin, 2005), an approach was proposed to explicitly include adsorption during pulse-decay method to measure the rock sample permeability. A sorption capacity term firstly derived by Dicker and Smits (1988) was implicitly introduced to correct the compressive storage in pore space at different pressures. Wang et al. (2011) used the original pulse-decay calculation method to measure the coal permeability and to quantify the sorption amount and sorption-induced strain under fixed stressed condition. These laboratory work advanced the understandings of the unconventional gas permeability measurements, but their laboratory conditions are not representative of true field conditions and consequently, the findings may be subject to faulty permeability measurements of sorptive-elastic media (Liu and Harpalani, 2014a, 2014b; Mitra et al., 2012).

Mitra et al. (2012) presented a step-wise laboratory permeability experiment under uniaxial condition, which replicates in situ condition of reservoir by fixing the lateral dimension and vertical stress. The application of uniaxial strain condition can interpret the dynamic changes of the state of stress during reservoir depletion (Liu and Harpalani, 2014c; Shi and Durucan, 2014; Shi et al., 2014). The uniaxial strain condition is widely accepted as in situ condition for subsurface reservoir development, in which the lateral boundaries of a reservoir are fixed and do not move, as well as the constant vertical stress due to the unchanged overburden (Geertsma, 1966; Lorenz et al., 1991). A reduction in reservoir pressure, in turn, results in a reduction in stress acting within and surrounding the reservoir. The horizontal stress acting in a reservoir at depth is observed to decrease significantly with decreasing reservoir pore pressure (Liu and Harpalani, 2014c). This stress decrease is known from simple theoretical calculations and has been observed in field for many conventional reservoir formations (Breckels and Eekelen, 1982; Teufel et al., 1991). In this study, permeability measurements were conducted on tight anthracite coal samples and different pulse-decay approaches were applied to figure out the feasibility of each method on unconventional reservoir rocks, with the evaluation of the permeability data under both constant stress condition and uniaxial strain condition.

### 2.4. Slip effect

Note that unconventional reservoir rock has very tight structure, gas flow in matrix is controlled by multiple flow dynamics including Darcy's