Gas permeability measurements on Australian subbituminous coals: Fluid dynamic and poroelastic aspects

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ARTICLE INFO

ABSTRACT

The interaction and the coupling of slip-flow of gases, a fluid dynamic phenomenon, and the cleat volume compressibility, a poro-elastic effect, have been investigated on two sister samples from the Taroom coal measure, Surat Basin, Queensland Australia. Measurements were performed using inert (helium and argon) and sorbing gases (nitrogen, methane and carbon dioxide) at different levels of controlled effective stress.

Apparent permeability coefficients decreased in the order helium $\gg$ argon $\gtrsim$ nitrogen > methane $\gg$ carbon dioxide. Even after slip-flow correction different permeability coefficients were obtained for the same sample and identical stress conditions when different gases were used as permeating fluids. These observations are inconsistent with the concept of "intrinsic permeability" which, as a material property, should be independent of the permeating fluid. Obviously the sequence of the "intrinsic" permeability is identical to the sequence of increasing non-ideality. Therefore, it should be considered that the classical Darcy equation, which is derived using the ideal gas law has a reduced validity for non-ideal gases like N_2, CH_4 and especially CO_2.

The cleat volume compressibility (stress-dependence of the intrinsic permeability) was evaluated using the "matchstick approach" (Robertson and Christiansen, 2008; Seidle et al., 1992). Cleat volume compressibility coefficients (c_f) are almost identical for the two samples at high mean pressure. However, for one sample a strong dependence of c_f on the mean pore pressure at low pore pressure was observed. This is attributed to a strong slip-flow effect caused by a narrow transport cleat system as compared to the sister sample. Cleat volume compressibility coefficients were nearly identical for inert and sorbing gases. The obvious strong coupling of slip-flow and poro-elastic properties is due to the generally "softer" behavior of coals in comparison to sandstones.

The occurrence of slip-flow in coals could, at least partly, compensate the reservoir permeability reduction resulting from increasing effective stress during the first depletion period (pressure draw-down). This should lead to a significant increase in productivity of coalbed methane reservoirs in the third production phase (pseudo-steady state phase; (GRI, 1996)). This conclusion appears to be also valid for shale gas and tight gas reservoirs, where the gas transport equally takes place in meso- and micropores.

1. Introduction

Gas storage and transport processes in coal beds are still poorly understood, mainly due to the complex nature of pore network of these unconventional natural gas resources. Pore networks in coals are characterized by a bimodal pore system: the coal matrix system, which mainly consists of micro- and meso-pores, and the cleat or fracture system comprising macro-pores and interconnected natural fractures (Harpalani and Schraufnagel, 1990; Yi et al., 2009).

Fluid conductivity in the pore network of coals is attributed to the conductivity of both, coal matrix and fracture systems. Due to the lower permeability of the matrix system, however, cleats and fractures are considered to be the principal avenues for gas transport and of particular importance from a coalbed methane (CBM) production perspective (Adeboye and Bustin, 2013; Gensterblum

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et al., 2011a, 2011b; Harpalani and Chen, 1997; Harpalani and Schraufnagel, 1990). Nevertheless, some studies have shown that, even when sufficient coal cleats and fractures are present, matrix permeability could be a limiting factor for CBM production in coal basins (Adeboye and Bustin, 2013). Understanding the factors that control matrix and fracture permeability of coals under effective stress is therefore of fundamental importance to the CBM and ECBM processes (Gensterblum et al., 2011a, 2011b).

Coal swelling and shrinkage, due to gas sorption and desorption, are dominant phenomena that significantly affect the coal reservoir permeability/productivity during primary and enhanced coalbed methane recovery (Palmer, 2004; Palmer and Mansoori, 1996; Shi and Durucan, 2004). The initial phase of gas recovery in CBM is usually dominated by water production which leads to fluid pressure drawdown. As pore pressure decreases, fracture permeability will also tend to decrease due to the increase of effective stress. This rapid initial reduction of fracture permeability is, however, accompanied by a slow permeability increase at a later stage of production that is commonly attributed to shrinkage of the coal matrix due to gas desorption. The fractures within the coalbed dilate and, in consequence, fracture permeability increases (Mazumder et al., 2012). Whether the long-term gas production rate is higher or lower than the initial rate depends on the net interaction of these two antagonistic mechanisms. In recent studies (Hol et al., 2014) it was found, however, that volumetric strain due to swelling under confined conditions did not exceed 1%. Therefore, the question arises if coal matrix shrinkage is able to produce permeability increases of a factor of 10 alone (Mazumder et al., 2012), or if additional effects have to be considered.

Many laboratory studies have been performed to evaluate the individual influences of effective stress and sorption-induced strains (swelling/shrinkage) on coal permeability (Astashov et al., 2008; Balan and Gumrah, 2009; Battistutta et al., 2010; Bromhal et al., 2004; Chen et al., 2010; Chern and Hayhurst, 2006; Cui et al., 2007; Day et al., 2008, 2011, 2010; Duffy et al., 2007; Durucan et al., 2009; Harpalani and Mitra, 2008; Jacobs et al., 2000; Karacan, 2007; Kelemen et al., 2006; Liu et al., 2011a; Mazumder et al., 2005, 2008; Mazumder and Wolf, 2008; Pan and Connell, 2007; van Wageningen et al., 2009; Wang et al., 2009, 2010, 2011). In general, these studies have shown that: 1) permeability coefficients measured using a non-sorbing gas decrease with increasing effective stress, and; 2) compared to non-sorbing gase, permeability coefficients measured with sorbing gases may decrease due to sorption-induced swelling/shrinkage (Pan and Connell, 2007; Pan et al., 2010). Apart from the effect of sorption-induced swelling/shrinkage, the coal permeability reduction observed when using sorbing gases could be partially due to differences in molecular diameters, i.e. molecular sieving effects (Cui et al., 2009). The molecular diameters of methane and carbon dioxide are significantly larger, than that of helium (Table 2), which may prevent them from flowing through permeability pathways accessible to helium.

In certain cases it has been observed, though, that permeability coefficients even increased when using sorbing gases (Chen et al., 2010; Mazumder et al., 2006; Mazumder and Wolf, 2008; Robertson and Christiansen, 2004). The results of previous studies, furthermore, suggest that sorbing gases (methane, carbon dioxide) induce very localized stress gradients (swelling/shrinkage) which may cause micro fractures (Hol et al., 2012).

2. Theory

2.1. Fluid flow regimes

Gas flow and transport in the cleat and matrix systems of coal beds occur on different characteristic time and length scales during CBM production. Several different transport mechanisms may proceed simultaneously, and the difficulty to describe the transition between two regimes of flow is, therefore, obvious (Amann-Hildenbrand et al., 2012). Furthermore, the changing effective stress regimes during production also influence the permeability. It is, nevertheless, possible to categorize these flow regimes into a number of broad categories. These flow regimes include turbulent non-Darcy flow in hydraulic fractures, Darcy flow in micro-fractures, macro- and meso-pores, slip flow in macro-, meso- and micro-pores and surface diffusion in meso- and micro-pores. Similar to organic-rich shales (Ghanizadeh et al., 2013; 2014), Darcy (pressure-driven volume flow) and slip flow regimes are expected to be the prominent mechanism of fluid (gas/water) transport within the micro-fractures, macro-, meso- and micro-pores of coal beds, and are therefore the focus of present discussion. Turbulent non-Darcy and diffusion flow regimes are beyond the scope of the present study.

2.2. Calculation of permeability (compressible fluid)

When a compressible fluid (gas) is used as permeating fluid, the expansion of the fluid along the flow path and the corresponding change in volumetric flow rate must be taken into account. Honoring the fact that the mass flux is constant along the sample and assuming isothermal conditions and the ideal gas law, Darcy's equation for compressible fluids can be derived: (Tanikawa and Shimamoto, 2006):

$$\frac{Q}{A} = -\frac{k}{\mu(p,T)\cdot L}\frac{(p_2^2 - p_1^2)}{2p_2} \tag{1}$$

Here p_1 and p_2 are the gas pressures (Pa) on the upstream and the downstream sides of the sample plug, respectively, $\mu(p_{mean}, T)$ is the dynamic viscosity in (Pa s) as a function of mean pressure p_{mean} and temperature T (calculated from the parameters in Table 1), L is sample length (m), A is the sample cross section area (m^2) and $Q = \Delta V / \Delta t$ the volumetric flow rate (m^3/s).

Table 1
Dynamic viscosity for the gases used at 35 °C (NIST webbook). The viscosity is calculated as a function of pressure at isothermal conditions. For the approximation we use a power series in P ($\mu = \mu 0 + \mu_1 P + \mu_2 P^2 + \mu_3 P^3 + \mu_4 P^4$).

Coefficients of power series for dynamic viscosity calculation	Argon	Helium	Nitrogen	Carbon dioxide[a]	Methane
$\mu 0$ (Pa s)	$2.316\cdot10^{-5}$	$2.029\cdot10^{-5}$	$1.825\cdot10^{-5}$	$1.541\cdot10^{-5}$	$1.149\cdot10^{-5}$
$\mu 1$ (Pa s /MPa)	$1.89\cdot10^{-7}$	$3.02\cdot10^{-8}$	$1.50\cdot10^{-7}$	$3.56\cdot10^{-8}$	$1.18\cdot10^{-7}$
$\mu 2$ (Pa s /MPa^2)	$8.76\cdot10^{-9}$	$1.15\cdot10^{-9}$	$4.46\cdot10^{-9}$	$6.041 0^{-8}$	$1.35\cdot10^{-9}$
$\mu 3$ (Pa s /MPa^3)	$6.33\cdot10^{-11}$	$-1.52\cdot10^{-10}$		$-1.11\cdot10^{-8}$	$-1.05\cdot10^{-10}$
$\mu 4$ (Pa s /MPa^4)	$-3.31\cdot10^{-12}$	$5.57\cdot10^{-12}$		$1.90\cdot10^{-9}$	$8.04\cdot10^{-12}$

[a] The CO$_2$ viscosity fit is valid up to 6 MPa.