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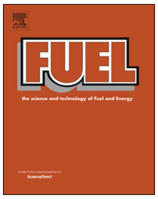

Full Length Article

Experimental study of impact of anisotropy and heterogeneity on gas flow in coal. Part II: Permeability

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ABSTRACT

Coal is highly anisotropic and heterogeneous, affecting coal permeability. As permeability is one of the most important reservoir properties for coalbed methane production, it is useful to understand the impact of coal anisotropy and heterogeneity on coal permeability. In this work, anisotropic permeability measurements were performed in the laboratory on three cubic samples from the same coal block from the Bowen Basin, Queensland, Australia. The permeability was measured at a series of gas and confining pressures. Cleat compressibility, a measure of permeability sensitivity to stress, was also calculated from the experimental results. Each sample was then scanned using microscopic X-ray computerised tomography after permeability measurements to study its cleat system. The results show that permeability is strongly anisotropic and heterogeneous among the three samples and is correlated with the cleat system. A permeability model, which incorporates stress, gas pressure and swelling effects, is used to describe the experimental results. At last, numerical simulations were conducted to demonstrate the impact of coal permeability heterogeneity on coalbed methane production.

1. Introduction

As one of the important unconventional gas resources, coalbed methane (CBM) has become an important industry in a few countries due to its huge reserves [1,2] and has significantly contributed to natural gas supply in these countries. For instance, China has estimated CBM resource of 36.81 trillion m^3 at depth shallower than 2000 m [3] and recoverable resource of 10.87 trillion m^3 [4] and it produced about 4.5 billion m^3 in 2016 [5]. Australia has huge CBM resource of about 5.8 trillion m^3 [6] and has become one of the largest CBM producers in the world. The proved and probable CBM reserves in Queensland, Australia was more than 1.0 trillion m^3 estimated in 2016 [7] and production reached 15.2 billion m^3 in the first six months in 2016 [8]. Meantime, CBM is also a hazardous gas in coal mining, thus extraction and utilization of CBM is one of the important aspects in coal mining safety [2].

The permeability of coal reservoir plays a central role for CBM drainage quality and quantity because most of the coal reservoirs have low permeability in the millidarcy (md) range [9,10]. Therefore, coal permeability has been widely studied either from the field or in the laboratory [11]. Coal permeability was often assumed to be isotropic, especially in the horizontal directions. However, coal has directional cleat system (the face and butt cleats) and bedding structure, past studies have shown that coal permeability is anisotropic [12–14]. The permeability anisotropy ratio between the perpendicular and parallel to bedding directions could be up to 1:17 from the field well tests on the Rock Creek coal seam of the Warrior Basin in the United States [12]. This strong permeability anisotropy and its dynamic change would impact significantly on the gas flow behaviour therefore the gas production or gas drainage rate. They are also useful to assist CBM well spacing planning or horizontal well drilling design [13,15]. Therefore, the anisotropic permeability of coal has been studied more extensively especially recently [16–19].

The main cause to coal permeability anisotropy is the existence of bedding planes [20] and the directional cleat system [21,22]. Coal is composed of matrix and natural cleats. It is commonly assumed that the

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Table 1
Vitrinite reflectance and the compositions of the three samples (from [34]).

	$R_{o,max}$ (%)	Proximate analyses (mass%)			Ultimate analysis (mass%)					
		Volatile	Carbon	Ash	C	O	Al	Si	Fe	N
Sample 1	0.90	1.51	88.6	9.9	84.4	9.3	1.7	1.7	1.7	1.1
Sample 2	1.02	1.54	72.9	25.5	77.8	14.1	3.1	3.3	0.6	1.1
Sample 3	1.05	1.58	83.0	15.4	81.6	13.1	1.5	1.6	0.7	1.5

permeability in coal matrix can be neglected compared with cleats [19,23,24]. The cleat system is widely distributed, comprising face cleats and butt cleats, both of which are oriented perpendicular to bedding plane [25,26]. Extensive and continuous face cleats are the main gas flow channels [21,22]. Less continuous butt cleats, usually perpendicular and end at face butts are also important flow path for gas in coal [26,27]. Therefore, permeability in the face cleat direction is higher than that in the butt cleat direction. Moreover, face cleats usually extend along the direction of maximum stress and the butt cleats develop along the direction of minimum stress [28,29]. It should be mentioned that the hydraulic factures tend to extend along the direction of maximum principle stress, which is the common direction of maximum principle permeability and face cleats.

Another major factor causing coal permeability anisotropy is the high degree of coal heterogeneity, which is resulted from a combination of many geological factors including sediment sources, depositional environments, tectonic settings, diagenesis, climate and hydrological conditions [30]. Coal composition has a strong heterogeneity in vertical direction. There are often interbedded rocks in coal seam due to geochemical interaction during diagenetic and metamorphic processes in the gradational contacted regions between the neighbouring waste rocks and the coal seam boundaries [31]. In horizontal directions, cleat system is also highly heterogeneous. Using X-ray computerised tomography scanning on 17 coal samples with varying degrees and types of mineralization recovered from Lower Permian and Upper Pennsylvanian strata in Qinshui Basin of China, Cai et al. [32] observed and measured details of cleat delineation and the result revealed that coal had a strong heterogeneity from the perspectives of cleat density. Moreover, they also found the internal cleat porosities varied from 0.06% to 20.69% after a stress was applied, indicating a strong internal heterogeneity thus permeability anisotropy. Furthermore, the heterogeneous distribution of mineral matter in the cleat system also has a fundamental effect on permeability anisotropy in coalbeds, for example abundant clay minerals may block gas flow path [32]. Through combining laboratory experiments and discrete element modelling, Guo et al. [33] concluded that the presence of calcite grains resulted the high mechanical and geometric heterogeneities of the coal samples they studied.

Although efforts have been paid to study the coal permeability anisotropy both in experiment and modelling, there is still need to improve the understanding, especially the impact of heterogeneity on anisotropy. Moreover, the cleat compressibility anisotropy was also rarely studied. However, these information help to predict coalbed permeability and its anisotropy evolutions and then the CBM production and drainage behaviours. In this work, a series of directional permeability measurements were performed on three cubic coal samples cut from the same Australian coal block using CH_4 at various gas and confining pressures. Cleat compressibility was calculated at each direction for each sample. Then cleat morphology and distribution inside the samples were investigated using microscopic X-ray computerised tomography scanning (X-ray μ-CT). Finally, the relationships of permeability, cleat compressibility and cleat distribution were discussed.

2. Experimental

2.1. Coal samples

Three cubic coal samples with length of 23 mm cut from the same coal block from the Leichhardt seam, Isaac Plains open cut mines in northern Bowen Basin, Queensland were used for permeability anisotropy measurements. These three samples were also used in the diffusion and adsorption study in [34]. The detailed process of cubic sample preparation can be referred to our previous work [35]. One principal direction of each sample is vertical to bedding plane and the other two are parallel to bedding plane. Horizontal direction 1 is the face cleat direction and horizontal direction 2 is the butt cleat for all three samples. The vitrinite reflectance and the compositions of the three samples are summarised in Table 1 and maceral composition results summarised in Table 2. These results show that the compositions are quite different among samples. The CT scanning images of the six faces for each sample are shown in Fig. 1. It can be seen that the structure and composition have significant differences among the samples. For Sample 1, there are two narrow mineral layers horizontal to bedding plane. For Sample 2, there are two mudstone layers and three mineral layers all horizontal to bedding plane. For Sample 3, there are extensive cleat network but most of them are filled with minerals. There are extensive cleats in each sample, and they will be further described in the discussion.

A 3D printed membrane was used to hold the cubic sample to simulate a cylindrical core, which can then be used in the tri-axial rig for permeability measurement. The details of the experimental technique can be refereed to our previous work [38]. Each of the three directions of the cubic sample can be installed in the 3D membrane to allow permeability measurement on different directions for the same sample.

2.2. Permeability measurement

The CH_4 adsorption measurements were descried in details in Part I of the present study [34]. After CH_4 adsorption reaching equilibrium, the permeability measurements were performed using the transient method [36], which was widely applied to low permeability measurements. A schematic of the apparatus is shown in Fig. 2. Before each

Table 2
Maceral composition results of the three samples (from [34]).

	Vitrinite (Volume %)			Liptinite (Volume %)				Inertinite (Volume%)				Minerals (Volume %)
	Telovitrinite	Detrovitrinite	Total	Sporinite	Cutinite	Liptodetrinite	Total	Semifusinite	Fusinite	Inertodetrinite	Total	Minerals
Sample 1	45.1	4.0	49.1	1.3	3.0	3.0	7.3	24.3	11.3	4.3	39.9	3.7
Sample 2	30.0	4.7	34.7	0.3	11.3	2.3	13.9	32.0	5.0	2.3	39.3	12.0
Sample 3	50.3	4.0	54.3	0.7	5.3	1.0	7.0	25.7	4.7	2.0	32.4	6.3